INTERFERENCE BETWEEN AN OSCILLATING-CYLINDER WAKE AND A NEIGHBOURING FLOW FIELD

Wing-cheong, Lai

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Certificate of originality

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written nor material which has been accepted for the award of other degree or diploma, except where due acknowledgement has been made in the text.

(Signed)...................................

Lai Wing Cheong

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ABSTRACT

This thesis presents an experimental study of fluid-structure interference. Two topics are covered.

Firstly, The flow behind two side-by-side tubes of identical diameter, *d*, one stationary and the other forced to oscillate in the lateral direction at an amplitude of A = 0.1 ~ 0.5d was examined. Two values of T/d, i.e. 2.2 and 3.5 were investigated, where T is the cylinder centre-to-centre spacing. The Reynolds number *Re* ranges from 150 to about 1000. The effect of forced oscillating amplitude A/d, spacing ratio T/d and frequency ratio f_e / f_s, (where f_e is cylinder oscillating frequency and f_s is the vortex shedding frequency of an isolated stationary cylinder), on the vortex shedding and the wake structure was examined. Specific attention was given to the occurrence of 'lock-in', where vortex shedding from the oscillating cylinder synchronizes with f_e. Significant influence of these parameters has been observed on the flow behind the cylinders in terms of the predominant vortex patterns and interactions between vortices. It has been found that the shedding frequency associated with the oscillating and the stationary cylinder can be modified as f_e/f_s approaches unity. Furthermore, the flow regime may change under the conditions of T/d = 2.2 and A/d = 0.5 from two distinct coupled streets to the combination of one narrow and one wide street. Subsequently, the lock-in state is considerably extended probably because multiple dominant frequencies in the asymmetrical flow regime can all be locked in with the structural oscillation.

Secondly, the effect of an oscillating cylinder on the flow in an alternately arranged 7-row array of 46 cylinders was investigated based on the laser-induced fluorescence flow visualization. The flow structure and vortex shedding frequency, without any cylinder oscillating, were in agreement with previous reports. As one cylinder in the first row was forced to oscillate laterally at an amplitude of A/d = 0.1 and

0.25 and frequency ratio f_e/f_s = 0.68 – 1.36, where f_s is the vortex shedding frequency when the cylinder was stationary, the 'lock-in' phenomenon occurred, that is, the shedding frequency of vortices from the oscillating cylinder synchronized with the oscillation frequency. The cylinder oscillation appreciably changed the flow structure, promoting vortex shedding from the oscillating cylinder and those downstream. It has been found that vortex shedding from the nearest two rows of cylinders downstream can be also locked in with the cylinder oscillation. When the oscillating cylinder was placed in the third row, the vortex shedding and cylinder-oscillating frequencies were decoupled at the lower end of f_e/f_s but locked in at the higher end. The effect of Reynolds number was also examined.

Two publications, including one refereed conference proceeding and one refereed journal papers, have been produced out of this work.

Contents

NOMENCLATURE

A	Cylinder oscillating amplitude	(mm)
i-j	Cylinder located at the i^{th} row and j^{th} column (for cylinder array)	
d	Diameter of circular cylinder	(mm)
f_s	Vortex shedding frequency of a stationary cylinder	(Hz)
f_e	Cylinder oscillating frequency of the forced oscillating cylinder	(Hz)
$f_{i\text{-}j}$	Vortex shedding frequency of cylinder at position of i^{th} row and j^{th} column (for cylinder array)	(Hz)
f_{s1}	Vortex shedding frequency of forced oscillating cylinder (Chapter 2)	(Hz)
f_{s2}	Vortex shedding frequency of stationary cylinder (Chapter 2)	(Hz)
L	Longitudinal center-to-center cylinder spacing	
P	Pitch	
Re	Reynolds number $\equiv U_\infty d / \nu$	
Re_g	Reynolds number $\equiv U_g d / \nu$	
St	Strouhal number $= f_s d / U_\infty$	
St_g	Strouhal number $= f_s d / U_g$	
t	time	(sec)
T	Transverse center-to-center cylinder spacing	
u, v	Streamwise and cross-flow fluctuation velocity, respectively	(m/sec)
U_∞	Velocity upstream of the cylinder array	(m/sec)
U_g	Gap flow velocity	(m/sec)
ν	Kinematic viscosity of fluid	(m^2/sec)
x, y	Co-ordinates in streamwise and lateral directions, respectively	
ρ	Fluid density	

ρ_p Correlation coefficient between spanwise fluctuating pressures

ϕ Phase

CHAPTER 1

INTRODUCTION

1.1 Background

Bluff body flows and their prediction are widely acknowledged as essential topic particularly in civil engineering. Vortex shedding from a bluff body is dominated by the dynamics in the flow low-pressure region and the feedback from the fluctuating wake (Naudascher 1987). For a stationary cylinder, this control leads to anti-symmetric vortex shedding. If the cylinder is forced to oscillate, vortex shedding will be influenced by movement-induced control that mainly depends on the combination of A/d and f_e/f_s (Karniadakis & Triataflyllou 1989), where f_e represents the oscillating frequency and f_s is the natural vortex shedding frequency of a stationary cylinder; A and d denote the oscillation amplitude and the diameter of cylinder respectively.

It is understood that using high-strength materials or the materials to limits, the structures become progressively lighter and more flexible. Thus, it is vital to eliminate or minimize the detrimental vibration. Structure like bridge, chimney, & high-rise building can be considered as a bluff body subjected to a cross flow where the flow separates from a large section of the structure surface. Flow-induced vibrations can cause fatigue that may fail the structures. One classical example is the collapse of the Tacoma Narrows suspension bridge (Figure 1-1) on 7 November 1940, due to wind-induced vibrations during a violent windstorm.

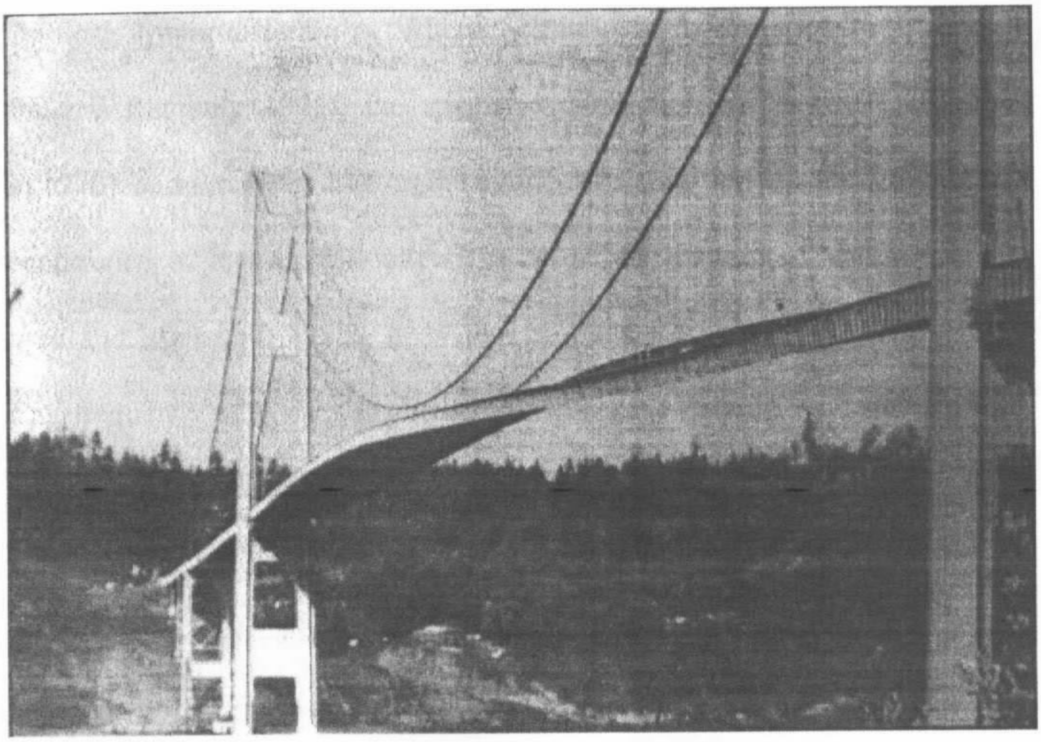


Figure 1-1 The Collapsing Tacoma Narrows Suspension Bridge

(From: http://www.civeng.carleton.ca/Exhibits/Tacoma_Narrows)

When bluff bodies are exposed to a uniform or unsteady flow, vortex shedding occurs and it creates fluid excitation forces acting on the structure. These unsteady forces will make the structures to vibrate (Sarpkaya 1979, Price *et al.* 1987; Weaver and Fitzpatrick 1988). The resultant structural motions may, in turn, change the flow field through the moving boundary conditions, thus giving rise to a change in the flow-induced forces, which will affect the vibration characteristics of the structure. Consequently, fluid and structure are coupled, modifying both the frequency and the magnitude of the forces on the structure.

The vibration behaviour of a bluff body impacts significantly on the wake characteristics of the structure. After the oscillation frequency of a transverse vibrating circular cylinder approaches the vortex shedding frequency of its wake, the vortex shedding frequency can be modified, resulting in $f_s = f_e$. This phenomenon is called 'lock-in' or 'synchronization'. When lock-in occurs, the strength of the vortices (Griffin and Ramberg 1975), the spanwise correlation of the wake (Ramberg and Griffin 1976), and the mean drag on the cylinder (Bishop and Hassan 1964) is increased. The occurrence of lock-in also alters the phase and pattern of vortices in the wake (Ongoren and Rockwell, 1988a, b; Williamson and Roshko 1988). When the vortex-shedding frequency of a vibrating structure equals the natural frequencies of the fluid-structure system, resonance will occur. The resonance will produce negative impacts on fatigue life of the structure. The wake characteristics of a single vibrating circular cylinder have been extensively discussed in the studies of Koopmann 1964; Griffin *et al.* 1972, 1974, 1975; Williamson and Roshko 1988; Ongoren and Rockwell, 1988a, b; Blackburn and Henderson 1999. The wake characteristics are interrelated to the cylinder oscillating frequency f_e, the vortex shedding frequency f_s of a stationary cylinder, and Reynolds number. Except the general knowledge of the lock-in phenomenon of a single circular cylinder, it is necessary to know how the flow around neighboring structures reacts when the lock-in phenomenon happens in the presence of neighbouring structures. The resulting forces and vortex shedding pattern may not be the same as those found in a single cylinder case.

Engineering structures subjected to a cross flow are often constructed with multiple slender structures, such as twin high-rise buildings, tower of post-tensioning bridges, chimneys (Figure 1-2), offshore pilings, heat exchangers in a power station (Figure 1-3), piping in nuclear plant, and tube bundle in heat exchangers & boilers.

Figure 1-2 A semi-submersible offshore drilling unit (Polar Pioneer) of Transocean Inc. (From: http://www.deepwater.com/fleetspecifications.cfm)

In order to prevent structural failure due to fluid-structure interactions of an array of structures, the vortex shedding or wakes properties should be identified. Flow-induced vibrations caused by vortex shedding from the structures are a common fluid structure interaction problem. It causes structural fatigue and even lead to drastic failure of the structures. The situation becomes more complicated with the presence of an identical neighbouring cylinder, such as in the case of two side-by-side cylinders and a cylinder array. Unfortunately, previous literature information explaining flow-induced vibrations on flexible cylinders where oscillation amplitude and frequency depends on fluid forces, structural dynamics, and their non-linear interactions, is not enough to understand the interactions between the structural oscillation amplitude & frequency and the interstitial flow on neighbouring cylinders. Further work should have done.

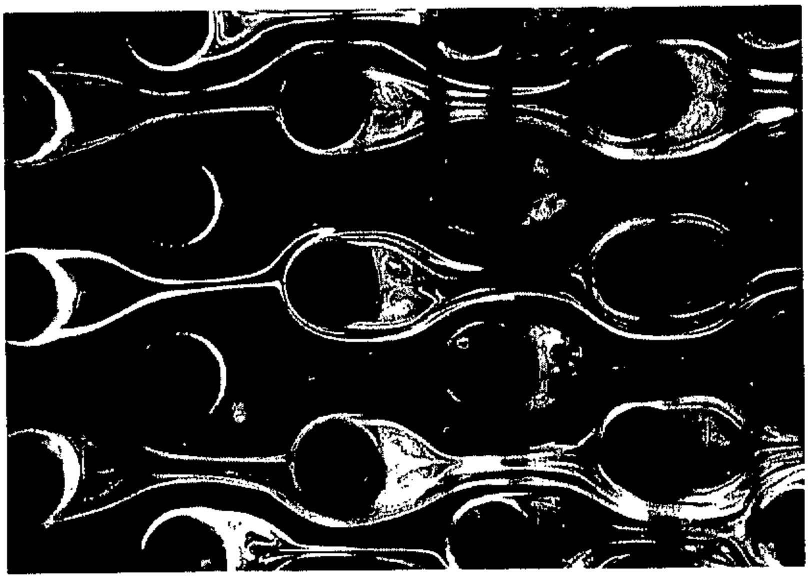


Figure 1-3 Flow in multi-tube heat exchangers of nuclear or thermal power stations (From ONERA's Science Pictures, http://www.onera.fr/photos-en/)

Present research works on fluid-structure interactions of a forced oscillating circular cylinder in a cross-flow with the presence of neighbouring stationary cylinders fall into two categories: (a) a forced oscillating cylinder with a stationary cylinder in side-by-side arrangement; (b) a forced oscillating cylinder on flow in a cylinder array. The effects of various parameters, including A/d, T/d, L/d, f_e/f_s and Reynolds number, will be discussed but more details will be given in lock-in phenomena.

1.2 A Brief Literature Review

1.2.1 Isolating oscillating cylinder in a cross flow

When a stationary cylinder is placed in a fluid flow, it is subjected to a fluctuating lift force, which acts in a direction perpendicular to that of the flow, and a fluctuating drag force that acts in the direction of flow. When the cylinder starts to oscillate, the flow structure will be changed significantly. Especially, when the cylinder oscillating frequency f_e approaches the natural vortex shedding frequency f_s, the two sets of forces become synchronized (Bishop and Hassan 1964). The system of cylinder and wake oscillates at the imposed frequency f_e of the cylinder only and the natural Strouhal frequency disappears. This phenomenon is called 'lock-in' or 'synchronization'. This lock-in persists over a range of frequency, and it will vary based on the amplitude ratio A/d and Reynolds number Re (Koopmann 1967; Griffin *et al.* 1972, 1974). Koopmann (1967) noted that the vortex shedding frequency could vary up to ± 25% for the same Reynolds number (<300). Moreover, from Griffin *et al.* (1972, 1974) investigation, the lateral spacing between vortices decreased as A/d increased which is due to the forced oscillation effect, but longitudinal spacing was unchanged. Various spatial modes of vortices generated by a oscillating cylinder at different A/d and f_e/f_s are observed and investigated by Williamson & Roshko (1988), the vortex synchronization in the wavelength-amplitude plane have explored. And from the investigation at various f_e/f_s the phase shift, recovery and mode competition in the near-wake for an oscillating cylinder of different cross sections (circular, square and triangular) of Ongoren & Rockwell (1988a,b), the vortex formation timing switched phase by almost 180° over a very narrow range of f_e when $f_e/f_s \approx 1$. Recently, Blackburn & Henderson (1999) investigated the 'lock-in' phenomenon of a single cylinder numerically, with a fixed oscillation amplitude $A/d = 0.25$, at $Re = 500$, respectively. The effect of variations in frequency ratio f_e/f_s on entrainment phenomena produced by forced oscillation within the primary lock-in regime was studied. They have been able to replicate the phase-switching behaviour observed in a number of experiments, and demonstrate that the switch is associated with a changing in sign of mechanical energy transfer between the cylinder and the flow.

1.2.2 Flow interference between two side-by-side cylinders

Because of practical needs, huge numbers of studies have aimed at the flow mechanisms of two side-by-side cylinders arrangement in cross-flow (e.g. Landweber 1942; Ishigai *et al.* 1972; Zdravkovich 1977; Williamson 1985; Chang and Song 1990; Sumner *et al.* 1999). Previous investigation found that the spacing ratio T/d is one of important parameters, which would have significant effects on the Strouhal number (vortex shedding frequencies), lift and drag coefficient, and wake pattern.

Whilst the cylinders are considered rigid bodies (with infinite structural stiffness) or stationary, in case $T/d > 6.0$, virtually no interactions are generated between the two Karman vortex streets (Landweber 1942). However, when $T/d < 6.0$, vortices shed from the two cylinders interact dynamically (Chang and Song 1990). In the range of $2.0 < T/d < 6.0$, vortices shed of each cylinder alternately at gap side and free-stream side with a frequency same as that of a single cylinder, a relatively small interaction between the two cylinders is indicated (Landweber 1942; Ishigai *et al.* 1972); both symmetrical (anti-phase) or anti-symmetrical (in-phase) vortex pattern from the two cylinders are observed (Chang and Song 1990); but the symmetrical vortex shedding is predominant over the anti-symmetrical vortex shedding (Ishigai *et al.* 1972; Williamson 1985). When the T/d is reduced to the range of $1.2 < T/d < 2.0$, "asymmetrical" flow; deflection of the gap flow and changeover are observed (Ishigai *et al.* 1972; Bearman and Wadcock 1973; Sumner *et al.* 1999). When T/d of the two side-by-side cylinders is further reducing to $T/d < 1.2$, no vortex is generated in the gap between the two cylinders; vortices are mostly alternately formed from the free-stream sides of the two cylinders with a frequency half of that of a single cylinder (Ishigai *et al.* 1972; Williamson 1985; Sumner *et al.* 1999).

Recently, the free vibration of two side-by-side elastic cylinders placed in a cross-flow and the associated non-linear fluid-structure interactions are investigated by Zhou *et al.* (2001) in detailed. Three *T/d* ratios, 3.00, 1.70 and 1.13, with respect to three different flow regimes, were investigated. Vortex formation and its evolution around the cylinders have been examined. At *T/d* = 3.0, the vortex pairs are formed symmetrically and shed from the two cylinders for a sufficiently large transverse spacing. The two vortex streets behind the cylinders are predominantly in the anti-phase mode, and independent of *Re*. At *T/d* = 1.7, one narrow and one wide wake were observed and the corresponding normalized dominant frequencies. The two vortices across the narrow wake displayed different convection velocity and subsequently underwent pairing. The two counter-rotating pairing vortices further acted to 'suck' in the gap vortex in the wide wake generated by the other cylinder. At *T/d* = 1.13, the spectral phase shift is generally near zero, indicating a dominance by the alternate vortex shedding, though symmetric shedding is seen from the flow visualization data from time to time. Moreover, due to the fluid-structure interactions, the natural frequencies of the combined fluid-cylinder system change; and vortex shedding dominates the nonlinear interaction between the fluid excitation force and the structural vibration in the free vibration case. Consequently, the systems' natural frequency is modified so as to adapt to the vortex shedding frequency when both frequency components approach each other.

1.2.3 Flow structure in cylinder array

From early studies on flow structure of stationary cylinder clusters and multi-tube arrays, Strouhal numbers data of stationary cylinder array from the literature has been collected and plotted by Chen (1968) and Fitz-hugh (1973); and Weaver *et al.*

(1987) established an empirical prediction rule for the frequency of vortex shedding from the second-row cylinders, i.e. $St = [1.73\ (P/d - 1)]^{-1}$ for $P/d \geq 2.0$. However, the Strouhal number may not keep in constant along the cylinder array. From the investigation of Weaver *et al.* (1993) on a rotated square tube array over a range of $P/d = 1.21{\sim}2.83$ as $Re = 696{\sim}19.6{\times}10^3$, two distinct Strouhal numbers were reported behind the first- and second-row, respectively, but the Strouhal numbers were found unchanged from the second to the sixth row, similar results is also observed by Polak and Weaver (1995) in normal triangle tube arrays when $P/d \geq 2.0$. It suggested that one reason for this might be that the local velocities and wake widths governing the vortex shedding are different. Weaver *et al.* (1993) suggested that if the Strouhal number is computed based on the flow velocity near the point of flow separation and minimum wake width, it appears that a unique Strouhal number for the array may be found. Moreover, when the total dynamic lift and drag coefficients are plotted as function of row depth by Ongören and Ziada (1998) in a normal triangular array, for P/d = 1.61, 2.08 and 3.41; a strong dependence of the force coefficients on the spacing ratio is observed. At a given row, the level of the lift and the drag coefficients increase gradually with increasing spacing ratio. Maximum level is reached around the second or third rows. Generally, the Strouhal number in a cylinder array is strongly dependent on P/d, measurement location, and the Re (Weaver *et al.* 1993, Polak and Weaver 1995 and Ongören and Ziada, 1998). As results, Strouhal number data are plotted in curve and compared with those from the literature as a function of pitch ratio by Weaver *et al.* (1993) and Polak and Weaver (1995).

As the flow-induced vibration is one of main fluid-structure interaction problem associated with a cylinder array in cross flow, such as heat-exchangers, past research has revealed that it may be attributed to four mechanisms: turbulent buffeting, fluidelastic instability, acoustic resonance, and vorticity shedding (e.g. Païdoussis, 1982; Chen, 1987; Weaver & Fitzpatrick, 1988). From previous literature, fluidelastic instability and acoustic resonance are two important problems of concern.

Firstly, regarding the fluidelastic instability problem in cylinder array, most researchers is placing a single flexibly supported cylinder in a cylinder array, with all otherwise cylinders are mounted rigidly. Previous literature found that the pitch ratio P/d has a significant effect on the fluidelastic instability of the flow structure. From Price *et al.* (1987), one flexibly supported cylinder in a seven-row rotated square array of otherwise rigid cylinders which subject to a cross-flow at P/d = 2.12, when the flexible cylinder was placed at different rows; although vibrating due to both turbulent buffeting and resonance with array-induced flow periodicities, the flexible cylinders did not become fluidelastically unstable. However, when the pitch ratio is reduced to $P/d <$ 2.0, fluidelastic instability occurs with the flexible cylinder in all rows of the arrays. For example, fluidelastic instability is observed in normal triangular array at P/d = 1.375 in Price and Zahn (1991), and, in-line square array at P/d = 1.5 in Price and Païdoussis (1989). From the review report of Price (1995) on the theoretical models for fluidelastic instability of cylinder arrays in cross-flow, it found that the unsteady nature of the interstitial flow in the array is the most important parameter for predicting fluidelastic; specifically, the phase-lag between cylinder motion and fluid forces generated thereby. The effect of non-linearities, both structural and fluid, on the post-instability behaviour is reviewed.

Secondly, the relationship between the mechanism of acoustic resonance and the nature of the flow periodicities is another important subject should be considered in flow-induced vibration problem. From the experiment of Ziada and Oengören (2000), in parallel triangle tube arrays with P/d = 1.21~4.17 at $Re_g = 9\times10^4$ in wind tunnel, and

P/d = 1.4, 2.08 and 3.41 in water tunnel; three different components of flow periodicities have been observed and have a detail studied. Especially, for the arrays with $P/d \leq 2.42$, the onset of acoustic resonance could not be related to the natural flow periodicities which are observed before the onset of resonance. This contrasts with the acoustic response of normal triangle arrays for which the resonance has been found to be excited by the natural flow periodicities. Moreover, the acoustic Strouhal number chart as function of P/d has been developed for parallel triangle arrays, it is useful for estimate the critical flow velocities corresponding to these Strouhal numbers. Instead, designer should ensure that the Strouhal number based on the maximum flow velocity and any acoustic frequency is higher than the design limit.

1.2.4 Issues identified

The fluid-structure interactions of two side-by-side cylinders have been widely acknowledged for the past fifty years (Landweber 1942; Ishigai *et al.* 1972; Bearman and Wadcock 1973; Chang and Song 1990; Sumner *et al.* 1999; Zhou *et al.* 2001). From there, we could understand more about the fluid-structure characteristics of two side-by-side cylinders subjected to a uniform cross-flow. Nevertheless, early efforts concentrated on the behaviour of the wake flow and the flow-induced vibrations on rigid cylinders. Even in the free vibration case, the cylinders, flexibly mounted at both ends, were relatively rigid. In the case that the neighbouring cylinder is forced oscillating, the influence on the flow is scarce.

It is important to know the possibility on the prediction of the fluid-structure characteristics for both forced oscillating cylinder and stationary cylinder by control the oscillating amplitude A/d and oscillating frequency f_e. For side-by-side cylinder arrangement, the distance between two cylinders, T/d, is one of critical parameters as it will create impacts on the flow structure. In the case of two side-by-side stationary cylinders, two distinct and coupled streets occur at $T/d \geq 2.0$, the symmetric vortex shedding predominant over the anti-symmetric shedding; or a bi-stable asymmetrical flow in the range of $1.5 \leq T/d \leq 2.0$, the physics behind the formation and stability of a narrow and a wide wake is unclear. In addition, it is interest to know how the coupling would be affected when one cylinder oscillated at different T/d and the possibility on the 'lock-in' phenomenon in a side-by-side cylinder arrangement.

From the literature review, it is still lack of information to make predictions in different mechanisms. For example, although Price *et al.* (1987, 1989, 1991) has provided valuable insights for the nature of fluidelastic instability, the use of a single flexible cylinder in a rigid array of tubes to model fluidelastic instability is not generally applicable; and, in particular, it is not valid for configurations in which the mass-damping parameter exceeds 300. There is only limited information showing how the structural oscillation amplitude and frequency would influence the interstitial flow in cylinder arrays. further works should be done to find out if the oscillation of a cylinder in an array modify vortex shedding from surrounding neighbouring cylinders and 'lock-in' phenomenon is corresponded, and to predict the fluid-structure characteristics of cylinders, not only the forced oscillating cylinder but also the neighbouring stationary cylinders in array.

1.3 Objectives

The primary goal of this research is to investigate experimentally the fluid-structure interactions of a forced oscillating circular cylinder in a cross-flow in the presence of a stationary cylinder in a side-by-side arrangement and a seven-row cylinder arranged in a triangular array. The focus will be on the oscillation effects on the flow structure and vortex shedding frequencies.

The specific objectives are stated as follows:

(i) To study the flow behind two side-by-side cylinders, one stationary and the other forced to oscillate in the lateral direction, subjected to a uniform cross-flow, the occurrence of 'lock-in' phenomena on both stationary and oscillating cylinder with respect to different parameters, A/d, T/d and f_e/f_s at Reynolds number range $Re = 150$ to 1000.

(ii) To investigate the change of flow structure for both stationary and oscillating cylinders, in side-by-side arrangement, due to the force oscillate of one of cylinder, especially at different T/d regime.

(iii) In the cylinder array case, to study the effect of the 'lock-in' phenomena not only on the forced oscillating cylinder, but also the effect on the vortex shedding frequencies of the neighbouring cylinders, with respect to parameters. A/d and f_e/f_s, when the oscillating cylinder is located on different position of array.

(iv) To investigate the change of flow structure on cylinder array, due to the force oscillate of one of cylinder in different position of cylinder array with respect to parameters A/d and f_e/f_s.

1.4 Thesis Outline

The rest of the thesis is organized as follows:

Chapter 2 presents the effect of a neighbouring vibrating cylinder on a circular cylinder wake using laser-induced fluorescence techniques. This chapter also discusses the dependence of the flow structure and vortex shedding frequencies on f_e/f_s, T/d and A/d.

Chapter 3 presents the effects of a laterally oscillating cylinder on flow in a cylinder array based on the LIF flow visualization. The dependence of the flow structure and vortex shedding frequencies on the location, A/d and f_e/f_s of the oscillating cylinder are also demonstrated.

Chapter 4 concludes the research work in this thesis.

CHAPTER 2

INTERFERENCE BETWEEN STATIONARY AND FORCED OSCILLATING VIBRATING CYLINDER WAKES

2.1 Introduction

The wake of a vibrating structure has received considerable attention in the literature because of its practical significance. One of the primary concerns is that the vortex-shedding frequency from a vibrating structure may synchronize with the natural frequencies of the fluid-structure system, which amplifies structural vibration amplitude and leads to a reduced life span of the structure or even early failure. Furthermore, the wake of one or more vibrating structures is of relevance to the prediction of forces on downstream structures.

In their early studies of a single forced oscillating cylinder in a cross flow, Bishop & Hassan (1964) observed that when the cylinder oscillating frequency f_e approached the vortex shedding frequency f_s of a stationary cylinder, the two sets of forces were synchronized, and the natural shedding frequency was lost, resulting in the so-called 'lock-in' phenomenon. Within the synchronization range, lift and drag forces varied in phase and amplitude with the imposed frequency. Koopmann (1967) noted that the 'lock-in' range, over which the vortex shedding frequency was dictated by f_e, was dependent on the amplitude ratio A/d and, to some extent, on the Reynolds number Re (based on d and the free stream velocity U_∞). The vortex shedding frequency could vary up to ± 25% for the same Re (< 300). Griffin *et al.* (1972, 1974) found that the 'lock-in' occurred for $f_e = 0.8 \sim 1.2 f_s$. They further observed that, due to the forced vibration effect, the lateral spacing between vortices decreased as A/d increased but the longitudinal spacing was unchanged. Williamson & Roshko (1988) discussed various spatial modes of vortices, generated by a vibrating cylinder at different A/d and f_e/f_s. Ongoren & Rockwell (1988a, 1988b) investigated at various f_e/f_s the phase shift, recovery and mode competition in the near-wake for an oscillating cylinder of different cross sections (circular, square and triangular). They noted that when $f_e/f_s \approx 1$, the vortex formation timing switched phase by almost 180° over a very narrow range of f_e. Numerical studies have also been conducted. For example, using a primitive-variable formulation on a spectral element spatial discretization, Blackburn & Henderson (1999) simulated a two-dimensional flow past a circular cylinder that was either stationary or in simple harmonic cross-flow oscillation at $Re = 500$, $A/d = 0.25$ and $f_e/f_s = 0.875 \sim 0.975$. They showed that the change in phase of vortex shedding is associated with a change in sign of mechanical energy transfer between the cylinder and the flow.

Previous studies have greatly improved our understanding of the flow behind a vibrating cylinder. In engineering, however, we are frequently faced with the problem of multiple vibrating cylinders instead of an isolated one. Numerous investigations have been conducted to understand the cylinder wake in the presence of a neighbouring cylinder. It is now well known that, when the cylinder centre-to-centre spacing ratio T/d is greater than 2, two distinct vortex streets occur behind the cylinders. The two streets are predominantly in antiphase mode (Ishigai *et al.* 1972). Nevertheless, the inphase vortex streets are also observed from time to time (Bearman & Wadcock 1973, Williamson 1985, Zhou *et al.* 2001). From the studied of Zhou & Antonia (1994), the critical points, such as vortex centres and the saddle points, of the two inphase streets are anti-symmetrical about the flow centreline, but symmetrical for the anti-phase case. At $1.5 \leq T/d \leq 2.0$, the gap flow between the cylinders is deflected, forming one narrow and one wide wake (Bearman & Wadcock 1973 and Summer *et al.* 1999). The deflected gap flow may change over intermittently from one side to another and is bi-stable. For very small spacing ratio, i.e. $T/d < 1.2$, vortices are alternately shed from the free-stream side only of the two cylinders, generating one single vortex street. Mahir & Rockwell (1996) investigated the wake of two side-by-side cylinders (T/d = 3.0), both forced to vibrate laterally. In the lock-in state, they observed a variety of flow patterns, which depended on the phase relationship between the two vibrating cylinders. The power spectral density function corresponding to the flow patterns was nevertheless almost the same. However, information on the flow when the neighbouring cylinder is vibrating is scarce.

This work aims to investigate interference between a stationary and a forced oscillating cylinder wake based on laser-induced fluorescence (LIF) flow visualization measurements. Great attention was given to the occurrence of 'lock-in'. Various parameters, including A/d, T/d and f_e/f_s, are investigated of their influence on the flow behind the cylinders in terms of the predominant vortex patterns, shedding frequencies and interactions between vortices.

2.2 Experimental Details

Experiments were carried out in a water tunnel with a square working section (0.15m × 0.15m) of 0.5m long. The water tunnel is a re-circulating single reservoir system (Fig. 2-1a). A centrifugal pump delivers water from the reservoir to the tunnel contraction. A honeycomb is used to remove any large-scale irregularities prior to the contraction. The flow speed, controlled by a regulator valve, is up to a maximum of about 0.32m/s in the working section. The working section is made up of four 20mm thick Perspex panels.

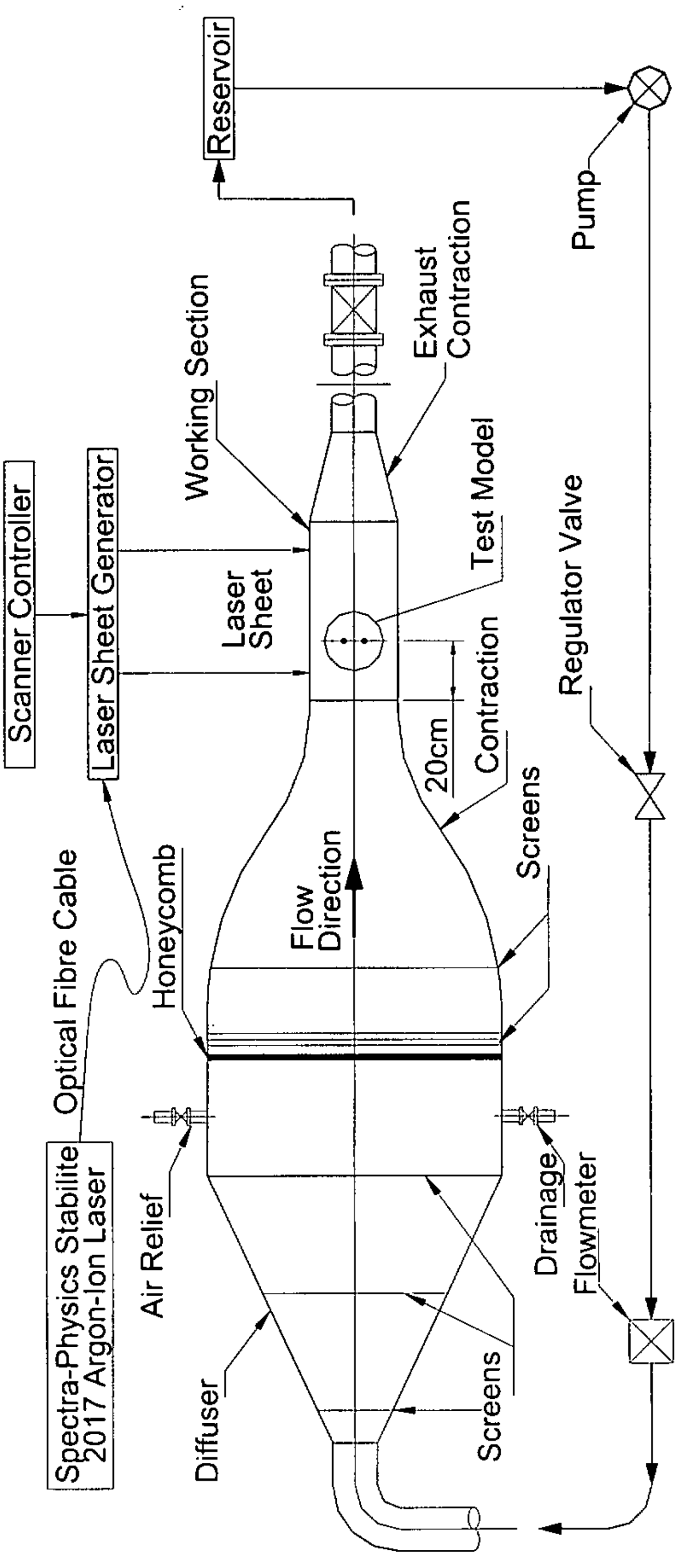


Figure 2-1a Schematic diagram of the water tunnel.

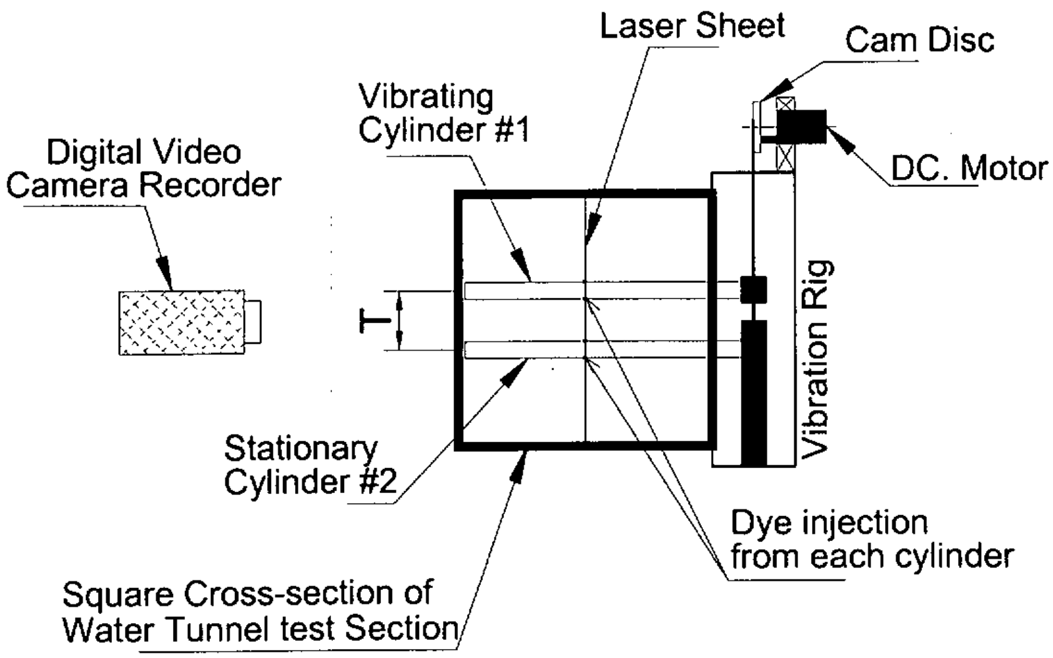


Figure 2-1b Cylinder arrangement in the test section.

Two side-by-side acrylic circular tubes of an identical diameter d = 0.01m, were horizontally mounted 0.20m downstream of the exit plane of the tunnel contraction and placed symmetrically about the mid-plane of the working section (Fig. 2-1b). The cylinders were cantilevered; there was a 1mm or so clearance between the cylinder free end and the tunnel wall. The resulting blockage was about 13%. The relatively high blockage may postpone the near-wake instability to a higher *Re* and further lead to the wake narrowing and subsequently rising Strouhal number, from the previous studies of Zdravkovich (1997), which are not the focus of the present investigation. Therefore, no correction was made for the blockage effect. The upper cylinder oscillated vertically at A/d = 0.1 and 0.5, respectively. The oscillation was provided by a D.C. motor through a cam-linkage system. The oscillation frequency, f_e, was measured by a tachometer (accuracy: ±5%) and confirmed by counting cylinder oscillation when playing back the real-time indexed video record. The f_e/f_s investigated varied between 0.74 and 1.44. In this chapter, f_s denotes the vortex shedding frequency of a single stationary cylinder (measured in the same tunnel), while f_{s1} and f_{s2} are the vortex shedding frequencies of the oscillating and the stationary cylinder, respectively.

Two transverse spacing ratios were used, i.e., T/d = 3.50 and 2.20, respectively. For stationary cylinders, three distinct flow regimes occur, depending on the T/d value, (Ishigai *et al.* 1972, Bearman & Wadcock 1973, Williamson 1985 and Zhou *et al.* 2001). Two distinct and coupled streets occur at $T/d \geq 2$; a bi-stable asymmetrical flow is observed for $1.5 \leq T/d \leq 2$. It is interesting to see how the coupling is affected when one cylinder oscillates and thus T/d = 3.5 was selected. It is equally interesting to see whether the flow regime could be changed, because of the cylinder oscillation, from two distinct coupled streets to the asymmetrical flow regime. Therefore, T/d = 2.2 was also investigated.

The cylinders have an aspect ratio of 15. For a stationary cylinder, an aspect ratio of 27 or larger is needed to avoid the end effects (King 1977). However, an oscillating cylinder may re-organize the vortex shedding process to enhance significantly its two dimensionality. Griffin (1980) observed that, when the oscillation amplitude was greater than 0.01~0.02d, the correlation coefficient, ρ_p, between spanwise fluctuating pressures increased greatly, compared with a stationary cylinder. For example, given a threshold of ρ_p = 0.5, the spanwise correlation length was about 1d at A/d = 0.025, 6d at A/d = 0.075 and 10d at A/d = 0.125. For A/d = 0.5, the correlation length is estimated to be over 40d based on an extrapolation of his data. It may be thus inferred that the end effect of the oscillating cylinder is negligible. Section 2.3 to 2.5 will show that vortex shedding from the stationary cylinder is also reorganized by the neighbouring oscillating flow, which enhances the two dimensionality of the flow, implying a small end effect for the stationary cylinder.

For each cylinder, dye (Rhodamine 6G 99%), which had a faint red color and became metallic green when excited by laser, was introduced through two injection pinholes at the mid-span of the cylinder. The pinholes were located around 90° away, clockwise and anti-clockwise, respectively, from the leading stagnation point. A thin laser sheet, which was generated by laser beam sweeping, provided illumination vertically at the mid-plane of the working section. A Spectra-Physics Stabilite 2017 argon ion laser with a maximum power output of 4 watts was used to generate the laser beam. A digital video camera recorder (SONY DCR-PC100E) was used to record, at a framing rate of 25 frames per second, the dye-marked vortex streets. Flow-visualization was carried out in the range of $Re = 150 \sim 1000$ over $0 \leq x/d \leq 8$. At larger Re and x/d, the dye diffused too rapidly to be an effective marker of vortices.

2.3 Vortex Shedding Frequencies

In the case of an isolated cylinder, the lock-in phenomenon occurred for the range of $f_e/f_s \approx 0.7 \sim 1.1$ at $A/d \approx 0.7$; this range narrows as A/d reduces (Mahir & Rockwell 1996b). When two inline cylinders were both forced to oscillate laterally in phase, vortex shedding from both cylinders was locked in with oscillation and the f_e/f_s range, where lock-in occurred, was almost the same as its single counterpart; however, if the two cylinders oscillated in anti-phase, the range was reduced significantly (Mahir & Rockwell 1996a). When two side-by-side cylinders were both forced to oscillate laterally, the lock-in range of f_e/f_s was narrower, particularly at relatively large A/d, than that of a single cylinder and shifted to a higher f_e/f_s (Mahir & Rockwell 1996b). It is of interest to explore whether vortex shedding from a stationary cylinder could be locked in when the cylinder interacts with a neighbouring oscillating cylinder.

Vortex frequencies were also estimated by playing back recorded data from the LIF flow visualization and counting consecutive vortices (about 100 pairs) at $x/d \approx 2$ for a certain period. The measurement uncertainty was estimated to be about 2%. The results are summarized in tables 2-1 to 2-5.

Firstly, a single forced oscillating cylinder (with identical diameter d = 0.01m) was horizontally mounted at the centerline of flow and investigated as a reference data for further comparison. The vortex shedding frequency f_{sI} of the forced oscillating cylinder can be 'lock-in' with the oscillating frequency f_e, i.e. $f_{sI} = f_e$, which is agreed with previous studied of Koopmann (1967) and Griffin *et al.* (1972, 1974). The results are summarized in tables 2-1.

Table 2-1 Vortex shedding frequency of isolating cylinder in stationary case f_s and frequency range of f_e/f_s when $f_{sI} = f_e$ at Re = 150~1000

Re	When $f_e = 0$	Frequency range of f_e/f_s when $f_{sI} = f_e$
150	f_s = 0.30 Hz	f_e/f_s = 0.94 to 1.28
300	f_s = 0.53 Hz	f_e/f_s = 0.94 to 1.41
500	f_s = 1.10 Hz	f_e/f_s = 0.74 to 1.18
1000	f_s = 2.05 Hz	f_e/f_s = 0.80 to 1.20

When the forced oscillating cylinder and another stationary cylinder were horizontally side-by-side mounted at the centerline of flow, the vortex shedding frequencies of both cylinders with respect to the forced oscillation are summarized in tables 2-2 to 2-5.

Table 2-2 Relationship between the oscillating frequency f_e and the vortex shedding frequency of oscillating cylinder and stationary cylinders (f_{s1} & f_{s2}). T/d = 3.5, A/d = 0.5; Re = 150~1000.

Re	f_e/f_s	f_e (Hz)	f_{s1} (Hz)	f_{s2} (Hz)
150	0.83	0.25	0.25	0.30
	1.00	0.30	0.30	0.30
	1.22	0.37	0.37	0.37
300	0.94	0.50	0.50	0.50
	1.19	0.63	0.63	0.58
	1.41	0.75	0.75	0.52
500	0.74	0.82	0.82	0.82
	0.96	1.06	1.06	1.06
	1.12	1.23	1.23	0.92
1000	0.80	1.63	1.63	1.63
	1.00	2.05	2.05	2.05
	1.20	2.47	2.47	2.47

Table 2-3 Relationship between the oscillating frequency f_e and the vortex shedding frequency of oscillating cylinder and stationary cylinders (f_{s1} & f_{s2}). T/d = 2.2, A/d = 0.5; Re = 150~1000.

Re	f_e/f_s	f_e (Hz)	f_{s1} (Hz)	f_{s2} (Hz)
150	1.00	0.30	0.30	0.30
	1.03	0.31	0.31	0.31
	1.28	0.38	0.38	0.38
300	0.95	0.51	0.77	0.82
	1.20	0.64	0.75	0.78
	1.44	0.77	0.77	0.77
500	0.76	0.83	0.83	1.05
	0.97	1.07	1.07	1.07
	1.15	1.27	1.27	1.27
1000	0.93	1.92	1.92	2.07
	1.11	2.28	2.28	2.28
	1.21	2.48	2.48	2.48

Table 2-4 Relationship between the oscillating frequency f_e and the vortex shedding frequency of oscillating cylinder and stationary cylinders (f_{s1} & f_{s2}). T/d = 3.5, A/d = 0.1; Re = 150~1000.

Re	f_e/f_s	f_e (Hz)	f_{s1} (Hz)	f_{s2} (Hz)
150	0.86	0.26	0.37	0.37
	1.03	0.31	0.40	0.33
	1.28	0.38	0.38	0.38
300	0.97	0.52	0.52	0.52
	1.19	0.63	0.63	0.48
	1.41	0.75	0.67	0.50
500	0.76	0.83	0.83	0.83
	0.95	1.05	1.05	0.88
	1.14	1.25	1.25	0.82
1000	0.80	1.63	1.63	1.63
	1.00	2.05	2.05	2.05
	1.20	2.47	2.47	2.47

Table 2-5 Relationship between the oscillating frequency f_e and the vortex shedding frequency of oscillating cylinder and stationary cylinders (f_{s1} & f_{s2}). T/d = 2.2, A/d = 0.1; Re = 150~1000.

Re	f_e/f_s	f_e (Hz)	f_{s1} (Hz)	f_{s2} (Hz)
150	0.89	0.27	0.32	0.35
	1.00	0.30	0.37	0.37
	1.22	0.37	0.37	0.37
300	0.97	0.52	0.58	0.57
	1.19	0.63	0.63	0.63
	1.41	0.75	0.75	0.75
500	0.76	0.83	1.23	0.90
	0.95	1.05	1.15	1.07
	1.14	1.25	1.25	1.25
1000	0.81	1.67	2.43	1.85
	1.02	2.08	2.13	2.12
	1.20	2.47	2.47	2.47

Firstly, at $T/d = 3.5$, f_{s1} is always equal to f_e for the f_e/f_s range investigated, that is, f_{s1} is modified and "lock-in" with f_e, as the isolated cylinder case (Table 2.2). This is not always the case for $A/d = 0.1$ (Table 2.4) since the lock-in range dwindles as A/d decreases (Koopmann 1967). As T/d reduces to 2.2, f_{s1} does not always follows f_e; instead, it may approach f_{s2}. The observation suggests that, when the stationary cylinder is in close proximity, f_{s1} is not only influenced by f_e but also by f_{s2}.

Secondly, the vortex shedding frequency f_{s2} of the stationary cylinder is not necessarily affected by f_e (Table 2-2~2.5). However, when f_e/f_s approaches unity, in particular, for $A/d = 0.5$, f_{s2} is inclined to follow the variation of f_{s1}, resulting in $f_e = f_{s1} = f_{s2}$. It is likely that the effect of 'synchronization', when f_{s1} is identical to f_e, is strongest at $f_e/f_s \approx 1$ so that f_{s2} is also modified and 'locked' in with f_{s1} or f_e. At $A/d = 0.1$, f_{s2} is less likely to be modified by f_e or f_{s1} even when f_e/f_s approaches unity because of the diminishing effect of 'synchronization' for smaller A/d.

From Lai *et al.* (2003) investigated, the investigation results from particle image velocimetry (PIV) and hot wires measurement are essentially consistent with the above observations from laser-induced fluorescence (LIF) measurement.

2.4 Typical Flow Structure

At $T/d = 3.5$, interference between the two streets appears relatively small in the immediate vicinity, perhaps up to $x/d \approx 5$, of the cylinders. This is illustrated in Fig. 2-2, where the two vortex streets behind one oscillating and one stationary cylinder (Fig. 2-2a) are compared with that behind a single oscillating (Fig. 2-2b) or stationary cylinder (Fig. 2-2c). The upper street (Fig. 2-2a) behind the oscillating cylinder appears rather similar to that (Fig. 2-2b) behind the single oscillating cylinder, and the lower street in the near-wake of the stationary cylinder resembles that (Fig. 2-2c) behind the single stationary cylinder. The similarity disappears for $x/d \geq 5$ as the two streets grow and their interference intensifies, which grossly increases the three dimensionality of the flow.

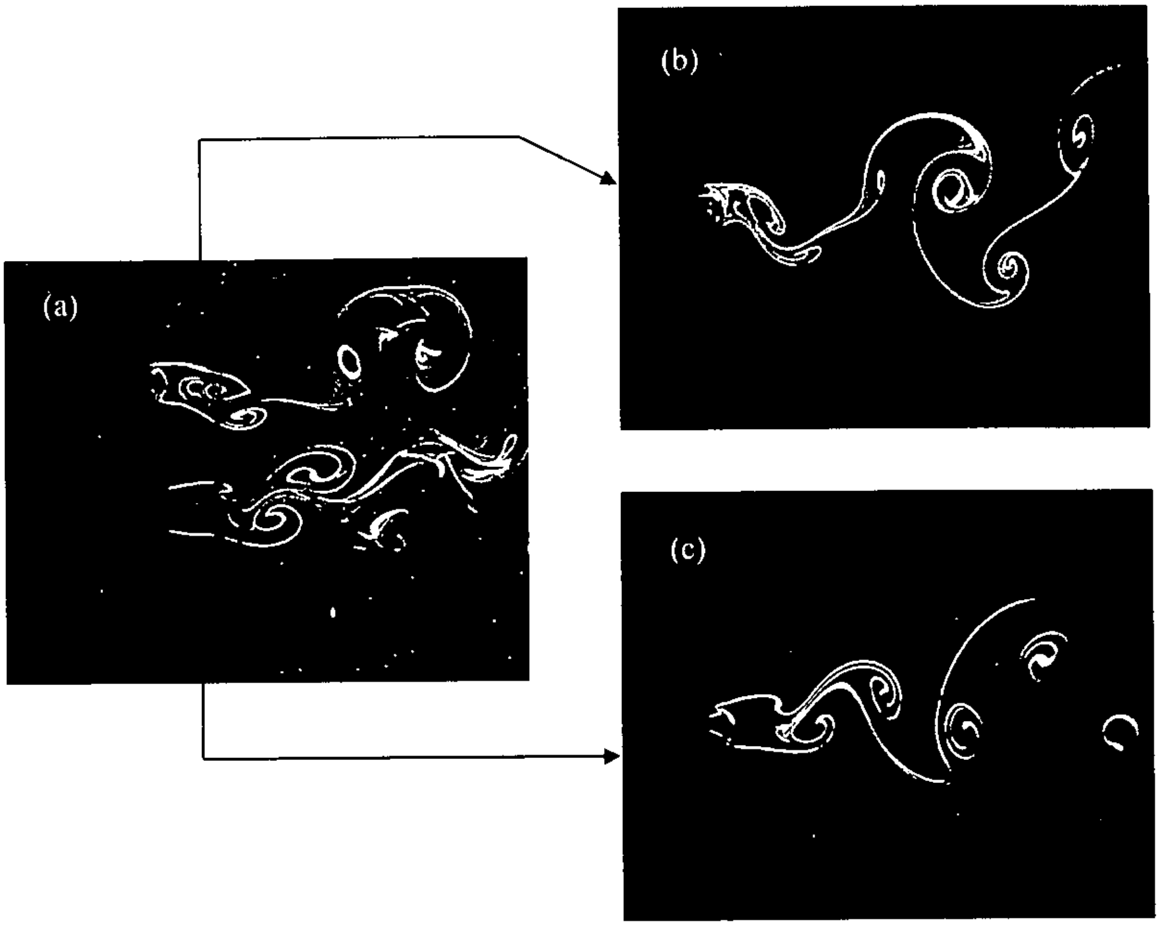


Figure 2-2 Comparison between vortex streets behind two cylinders and those behind an isolated cylinder: (a) T/d = 3.5, A/d = 0.5, f_e / f_s = 0.83; (b) an isolated vibrating cylinder, A/d = 0.5, f_e / f_s = 0.83; (c) an isolated stationary cylinder. Re = 150.

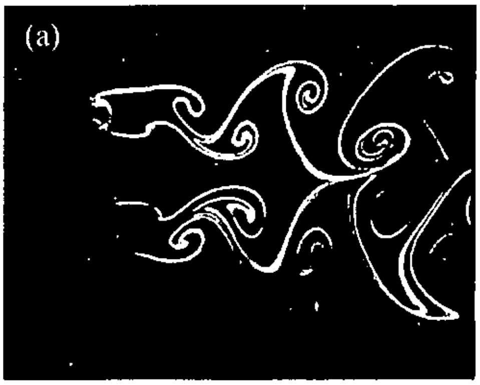
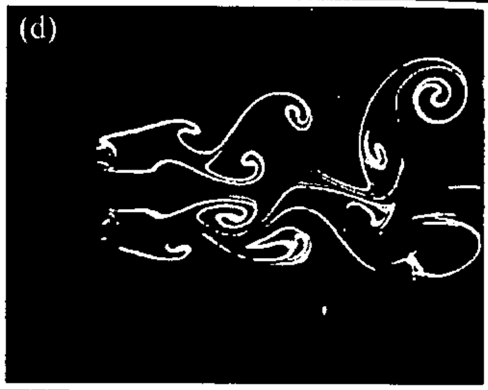
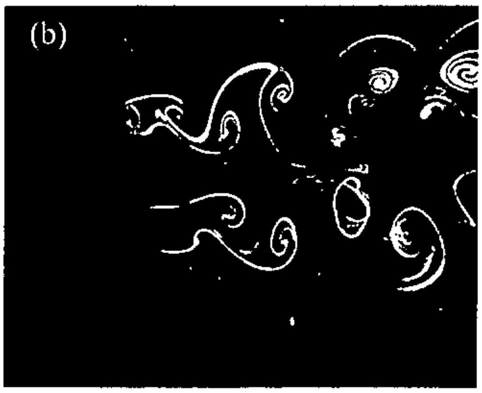
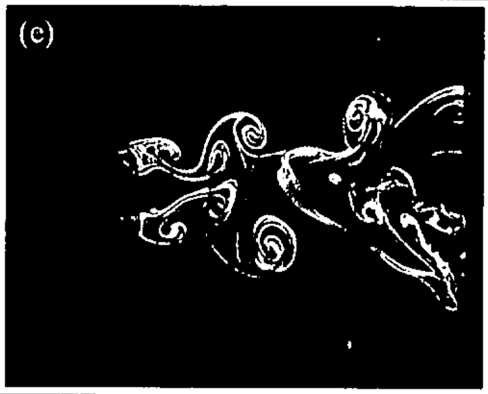
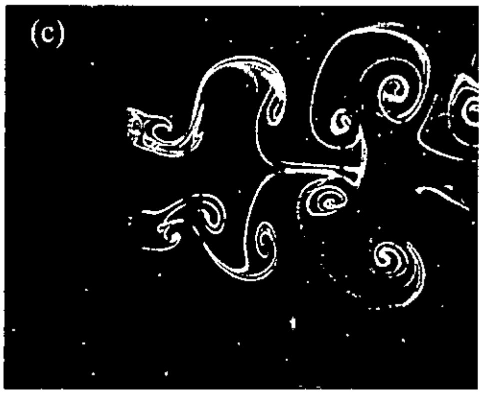
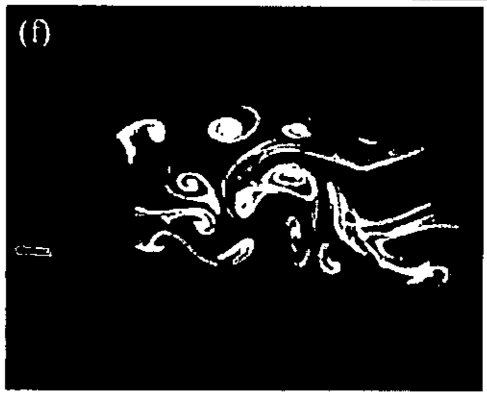
A/d	f_e/f_s	$T/d = 3.5$	$T/d = 2.2$
0	0		
0.1	1.2		
0.5	1.2		

Figure 2-3 Vortex streets behind two cylinders at different vibration amplitude: (a) $T/d = 3.5$, $A/d = 0$, $f_e/f_s = 0$; (b) 3.5, 0.1, 1.28; (c) 3.5, 0.5, 1.22; (d) 2.2, 0, 0; (e) 2.2, 0.1, 1.22; (f) 2.2, 0.5, 1.28. $Re = 150$, $f_{s1} = f_{s2}$.

The two streets behind the cylinders, shown in Fig 2-3, are symmetrical about the flow centreline or in the antiphase mode, irrespective of the vibration amplitude of the upper cylinder, as in the stationary cylinder case (Ishigai *et al.* 1972, Bearman & Wadcock 1973 and Zhou *et al.* 2001). But the inphase streets are also observed from time to time and can be stable. Furthermore, the oscillation of the upper cylinder tends to increase the wake width as A/d increases. Note that the lateral spacing between vortices generated by the oscillating cylinder will decrease as A/d increases (Griffin *et al.* 1972, 1974). The flow structures in Fig 2-3b and 2-3c are closely similar to those when both cylinders were forced to oscillate at a phase shift of 0° and 95° observed by Mahir & Rockwell (1996b).

As T/d reduces to 2.2 (Fig. 2-3d~f), the interaction between the two streets is expected to intensify, especially for large A/d. For stationary cylinders (Fig. 2-3d), two distinct streets are evident and predominantly symmetrical about the flow centreline. Present data also show the occurrence of in-phase streets (not shown), as previously reported (Bearman & Wadcock 1973). The two configurations for vortex streets are observed when the upper cylinder oscillates. The effect of cylinder oscillation is dependent on the configurations of vortex streets. For vortex streets in the antiphase mode, the oscillation acts to intensify the vortex interaction and to destabilise the two streets. Consequently, the two streets break up sooner, in particular at small T/d (compare Fig. 2-3e, f with Fig. 2-3b and c). On the other hand, the two streets in phase typically start to merge into one at a downstream distance close to the cylinders (see the following subsection 2-5 for more details). The above typical flow structures were also observed for a higher Re (up to 1000 in the present LIF flow visualisation data) in the turbulent flow regime (not shown), indicating an independence of Re in the range examined.

One vortex street in Figs. 2-3e and 2-3f appears rather narrow, compared with the other. This is more evident at A/d = 0.5 (Fig. 2-3f), in support of the earlier proposition that the cylinder oscillation could reduce effective spacing between cylinders, thus causing the formation of one narrow and one wide wake even at T/d =

2.2.

2.5 Change in the Phase Relation Between the Two Streets

It is of fundamental interest to understand why the two streets may change from antiphase to inphase. For two side-by-side cylinders of relatively large spacing, i.e. $T/d > 2$, two distinct coupled vortex streets occur from the early studied of Landweber (1942). Based on flow-visualization data at $Re = 100 \sim 200$, Williamson (1985) demonstrated that the two streets may occur in phase or in antiphase. The in-phase streets eventually merged downstream to form a single street, while the in-antiphase streets remained distinct farther downstream. He observed a predominant antiphase vortex shedding for $2 < T/d < 6$. However, it is not clear what triggers the transition of the two vortex streets from antiphase to inphase or vice versa.

Fig. 2-4 presents sequential photographs for $Re = 150$ and $A/d = 0.1$. The real time index is indicated by the first two numbers on the lower left-hand corner in the photographs and the sequential order is given by the third number. The vortex formation from the two cylinders is initially symmetric (Fig. 2-4a). One gap vortex *A* generated by the oscillating cylinder approaches the opposite-signed vortex *B*, which was shed from the free-stream side of this cylinder. It is apparent that *A* and *B* are engaged in a pairing process (Fig. 2-4a~d). Similarly, the following cross-stream vortices *C* and *D* also approach each other (Fig. 2-4d~g). This pair of counter-rotating vortices at close proximity is likely to generate a low-pressure region between them. The low-pressure region is responsible for drawing in the gap vortex *E* shed from the lower stationary cylinder, which lags behind *A*, thus resulting in the amalgamation of vortices *C*, *D* and *E* (Fig. 2-4d~g). Note that the amalgamation of the three vortices acts to slow down vortex *F* and subsequently *G* and *H* (Fig. 2-4d~g). Eventually, the anti-symmetrical vortex formation emerges (Fig. 2-4h) as a result of vortex interactions.

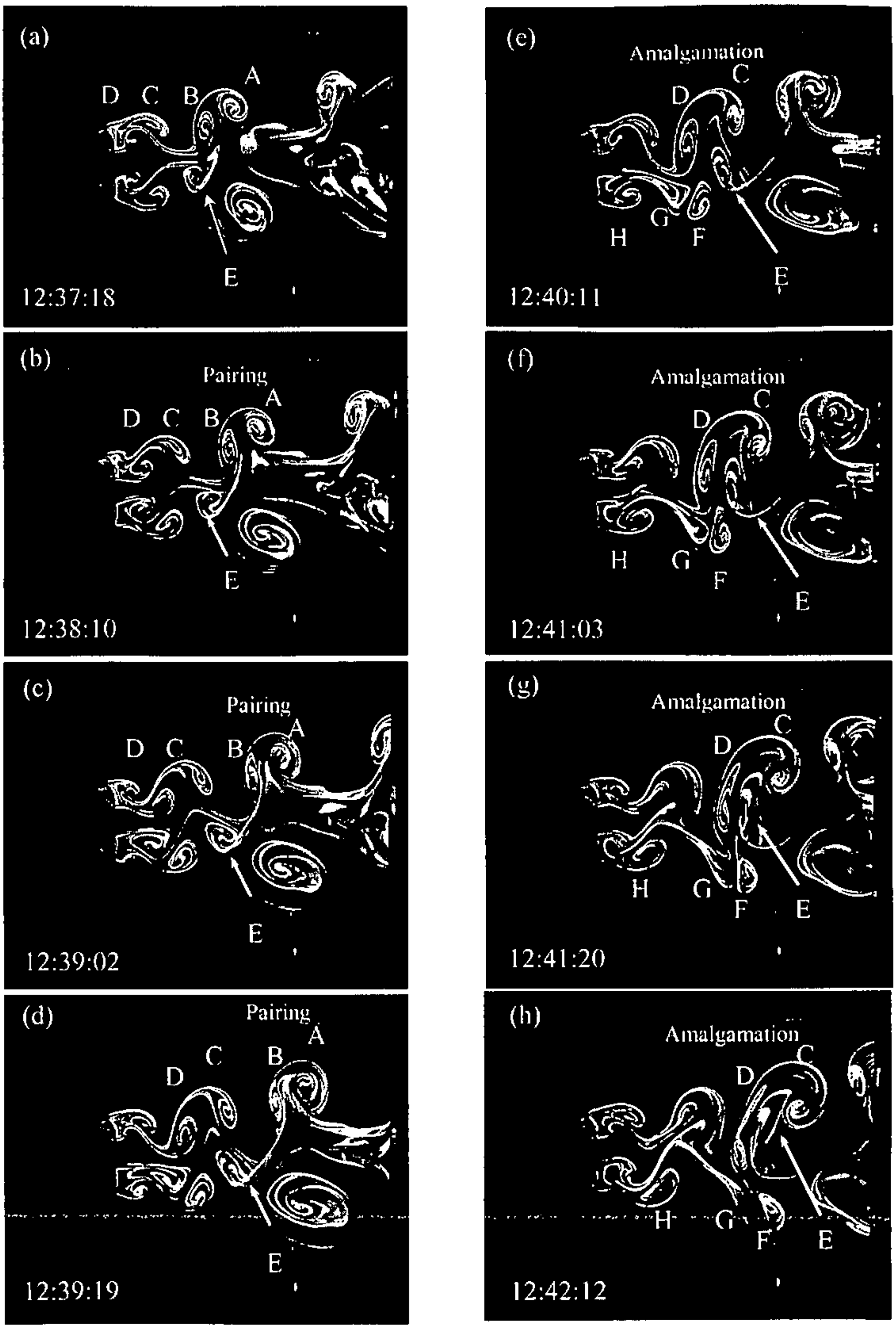


Figure 2-4 Sequential photographs of flow visualization: the occurrence of two pairing vortices followed by the merging of two cross-stream vortices shed from the oscillating cylinder with the inner vortex from the stationary cylinder. Meanwhile, symmetrical vortex shedding changes to the anti-symmetrical one. $T/d = 2.2$, the upper cylinder is oscillating at $A/d = 0.1$, $f_e/f_s = f_{s1}/f_s = f_{s2}/f_s = 1.22$, $Re = 150$.

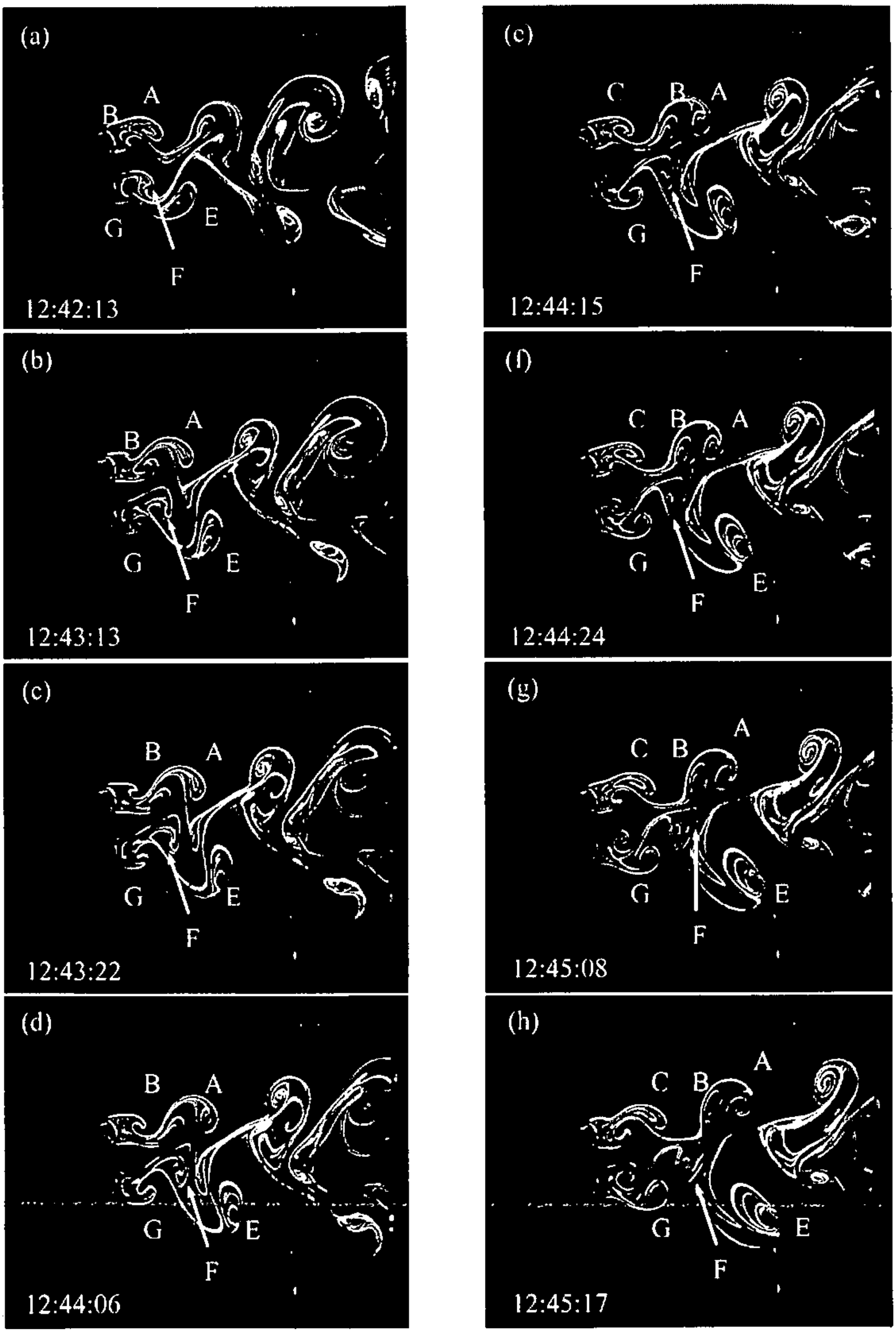


Figure 2-5 Sequential photographs of flow visualization: the merging of two cross-stream vortices shed from the oscillating cylinder with the inner vortex from the stationary cylinder. Meanwhile, anti-symmetrical vortex shedding changes to the symmetrical formation. T/d = 2.2, the upper cylinder is oscillating at $A/d = 0.1$, $f_e/f_s = f_{s1}/f_s = f_{s2}/f_s = 1.22$, $Re = 150$.

The anti-symmetrical vortex shedding did not last long and would soon revert to the symmetrical vortex formation. Sequential photographs (Fig. 2-5) following those in Fig. 2-4 indicate that vortices *A* and *B* appear pairing (Fig. 2-5d~h). Due to the low-pressure region formed between them, *A* and *B* manage to pinch fluid from vortex *F* in the lower street, but they fail to draw in vortex *F*. Apparently, *F* travels at an appreciably slower velocity. Meanwhile, vortices *E* and *F* behind the stationary cylinder appear approaching each other, though not pairing up. This may again produce a low-pressure region between them. Consequently, fluid in the upper street is assimilated to vortex *E* (Fig. 2-5b~h). This process is associated with a slowdown of the subsequent vortices (e.g. vortices *F* and *G*), thus leading to a symmetric vortex shedding (Fig. 2-5h).

It is interesting to note that the pairing of two vortices or the amalgamation of three vortices leads to the formation of a single vortex street downstream, which is probably asymmetrical. The observation bears resemblance to that behind two stationary cylinders. In the asymmetrical flow regime, i.e. T/d = 1.5 ~ 2.0, where a combination of one wide and one narrow wake occurs, Zhou *et al.* (2001) showed the amalgamation of the two cross-stream vortices in the narrow wake with the gap vortex in the wide wake. Subsequently the two streets merge into one. The resemblance further supports the earlier suggestion that the vibration of one cylinder could induce the change of the flow regime from two distinct vortex streets to one wide and one narrow streets at a T/d value greater than 2.0.

One remark could be made on the vortex interaction effect on the convection velocity of vortices. In order to highlight this point, a few photographs in Fig. 2-4 are re-plotted in Fig. 2-6. Evidently, the low-pressure region between pairing vortices *C* and *D* draws in and hence slows down *E*. On the other hand, *B* may have been accelerated due to pairing *A* and *B*. Consequently, *B* and *E* were travelled at different velocities. In contrast, the gap vortices, say A and B in Fig. 2-7, do not show appreciable difference in their convection velocity when the vortex pairing or amalgamation is absent. The flow structures corresponding to Fig. 2-6 and 2-7 are summarized in Fig. 2-8a and 2-8b, respectively. Zhou *et al.* (2002) measured the turbulent wake (x/d = 10 – 40) behind two side-by-side cylinders (T/d = 1.5 and 3.0) using a 3-wire probe (one cold wire plus one X-wires). The phase-averaged sectional streamlines and vorticity contours at T/d = 1.5 showed two rows of vortices, asymmetrically arranged about the flow centreline. The average convection velocity, estimated at x/d = 10, differed by about 10% between the two rows of vortices. It was however not quite clear what was responsible for this difference. The present observation (Fig. 2-6 and 2-7) suggests that the interaction between vortices could be partially responsible.

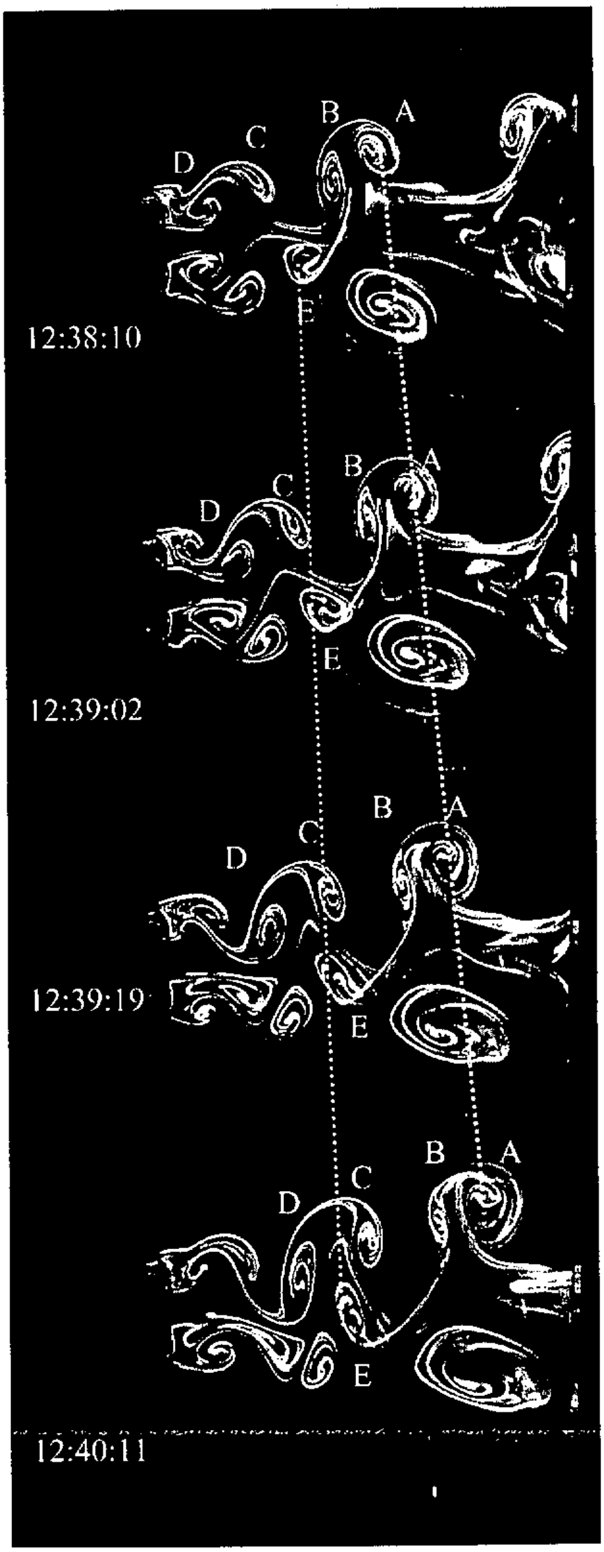


Figure 2-6 Sequential photographs of flow visualization: vortex interaction leads to a difference in the convection velocity between the inner vortices shed from the two cylinders. $T/d = 2.2$, the upper cylinder is oscillating at $A/d = 0.1$, $f_e/f_s = f_{s1}/f_s = f_{s2}/f_s = 1.22$, $Re = 150$.

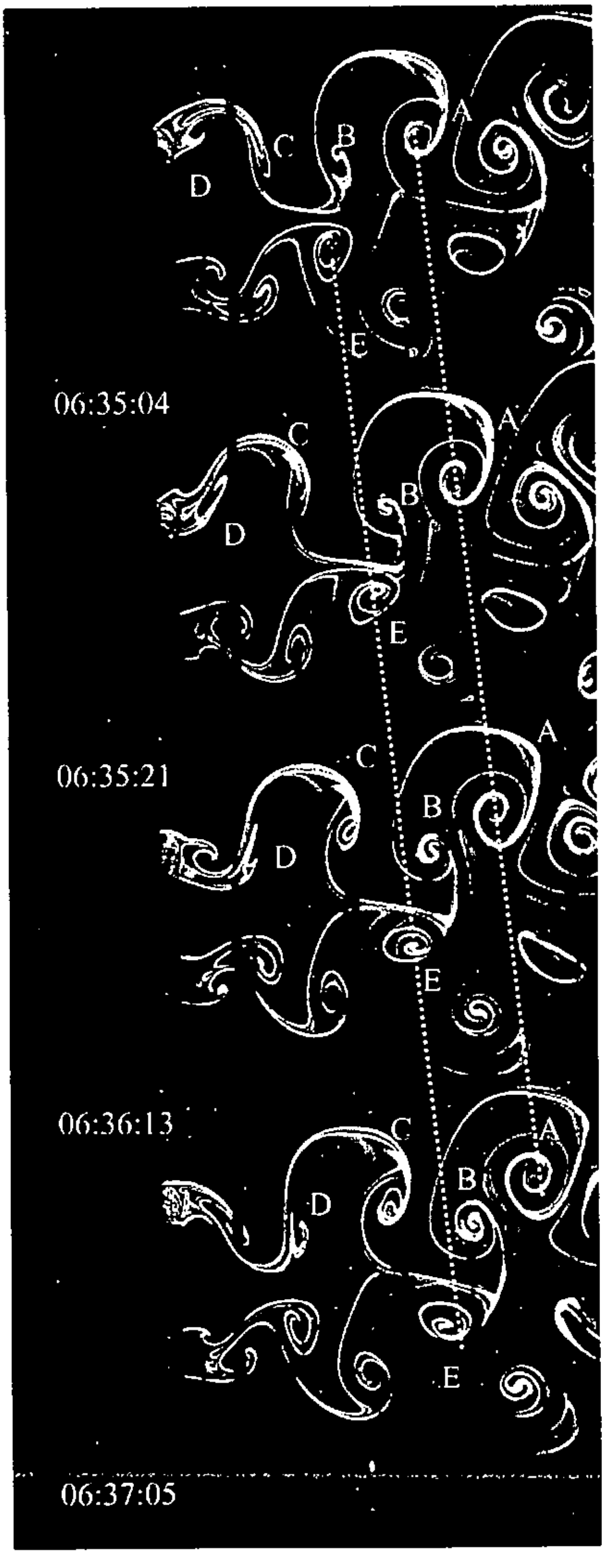


Figure 2-7 Sequential photographs of flow visualization: the same convection velocity for the inner vortices shed from the two cylinders. T/d = 3.5, the upper cylinder is oscillating at $A/d = 0.5, f_e/f_s = f_{s1}/f_s = f_{s2}/f_s = 1.22$, Re = 150.

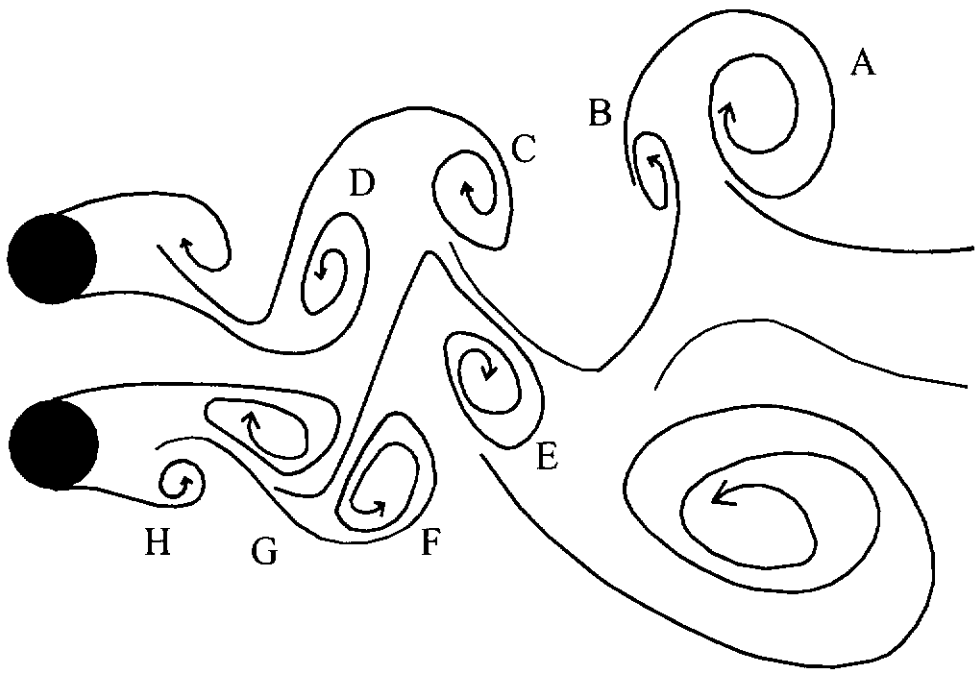


Figure 2-8a Summary sketch of figure 2-6, $T/d = 2.2$, the upper cylinder is oscillating at $A/d = 0.1$, $f_e/f_s = f_{s1}/f_s = f_{s2}/f_s = 1.22$, $Re = 150$.

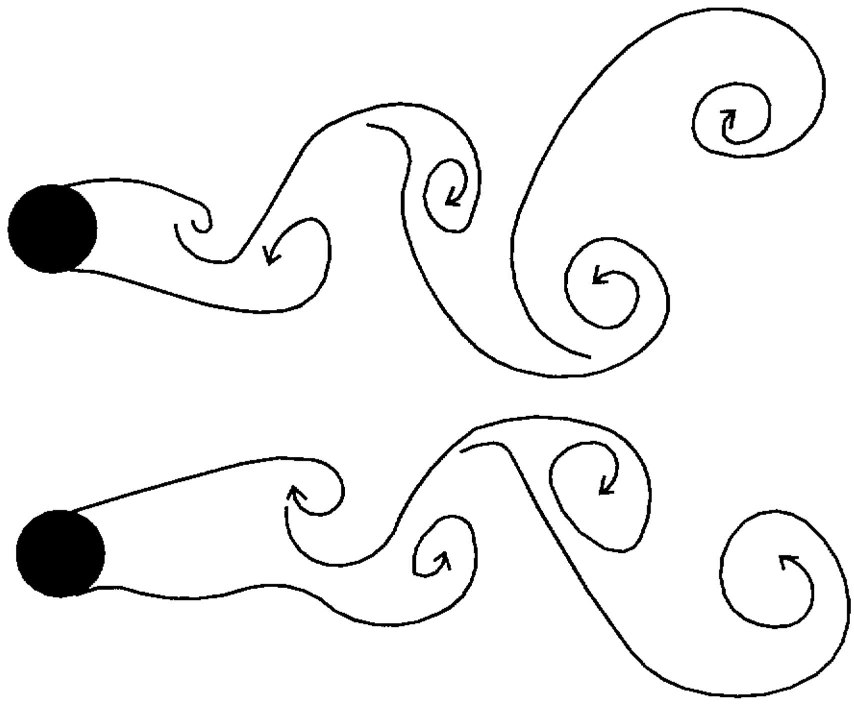


Figure 2-8b Summary sketch of figure 2-7, $T/d = 3.5$, the upper cylinder is oscillating at $A/d = 0.5$, $f_e/f_s = f_{s1}/f_s = f_{s2}/f_s = 1.22$, $Re = 150$.

2.6 Conclusions

The effect of a neighbouring vibrating cylinder on a circular cylinder wake has been investigated using laser-induced fluorescence techniques. The dependence of the flow structure and vortex shedding frequencies on f_e/f_s, T/d and A/d is examined. The following conclusions could be drawn.

1. For $T/d = 3.5$, the vortex shedding frequency f_{s1} of the forced oscillating cylinder can be 'lock-in' with the oscillating frequency f_e, i.e. $f_{s1} = f_e$, the same as in the case of an isolated cylinder (Griffin *et al.* 1972, 1974). The f_e/f_s range of lock-in is comparable with that for a single cylinder but larger than that for two oscillating side-by-side cylinders (Mahir & Rockwell 1996b). At the lock-in state, the vortex shedding frequency f_{s2} of the stationary cylinder may also be modified, resulting in $f_e = f_{s1} = f_{s2}$. In general, vortex shedding from the stationary cylinder becomes locked in with f_e later than that from the oscillating cylinder but decoupled earlier.

2. When T/d reduces to 2.2, the f_e/f_s range of lock-in increases very significantly at $A/d = 0.5$. The cylinder oscillation at such large amplitude acts to reduce effective spacing between cylinders and to change the flow regime from two distinct vortex streets to one wide and one narrow street. The lock-in of the multiple instability frequencies in the asymmetrical flow regime with the oscillation frequency is probably responsible for the extended lock-in.

3. At $T/d = 2.2$, the two streets do not seem to be stable as a result of the oscillating cylinder. The oscillation effect depends on the mode of vortex streets. For in-antiphase mode streets, the cross-stream inner vortices interact strongly and consequently break up quickly. A single street probably emerges further downstream. For in-phase mode streets, the two cross-stream vortices behind the

oscillating cylinder tend to pair. The pairing vortices are likely to induce a low-pressure region between them, thus drawing in the gap vortex generated by the stationary cylinder. The amalgamation of the three vortices leads to the formation of a single vortex street downstream, which is probably asymmetrical. The observation is consistent with the occurrence of the asymmetrical flow regime, which has been extended beyond that for the stationary cylinders because of the oscillation of one cylinder.

4. The amalgamation of the gap vortex shed from the stationary cylinder with two cross-stream vortices generated by the oscillating cylinder acts to slow down the subsequent vortices shed from the stationary cylinder. As a result, the in-antiphase vortex formation changes to the in-phase formation. Similar vortex interaction is associated with the variation from the in-phase vortex formation to the in-antiphase streets.

5. Two symmetrically formed gap vortices may have been convected at different velocity. The convection velocity of the gap vortex shed from the stationary cylinder was reduced due to the amalgamation of this vortex with two cross-stream vortices generated by the oscillating cylinder. On the other hand, the gap vortex shed from the oscillating cylinder could be accelerated in the process of pairing with the cross-stream outer vortex.

CHAPTER 3

EFFECT OF AN OSCILLATING CYLINDER ON FLOW IN A CYLINDER ARRAY

3.1 Introduction

An array of cylinders subjected to cross-flow is frequently seen in engineering, for example, tube banks in heat exchangers, chimney stacks, offshore structures and cooling-tower arrays. One problem often associated with such engineering structures is flow-induced vibrations, which can reduce the fatigue life of structures or even cause the structural failure, resulting in lost revenue and high repair costs. In order to improve our predictive abilities, it is essential to have a thorough understanding of underlying fluid dynamics.

Flow in an array of stationary cylinders has been a hot topic in the literature. Great attention was given to the Strouhal numbers (e.g. Chen 1968; Fitz-hugh 1973). In in-line square arrays, the Strouhal number was found to be largely dependent upon the longitudinal pitch ratio of the array (Weaver and Fitzpatrick 1988). In a rotated square tube array, two distinct Strouhal numbers were reported behind the first and second row, respectively, over the pitch ratio of P/d = 1.21 ~ 2.83 (Weaver *et al.* 1993), but the Strouhal numbers were found unchanged from the second to the sixth row (Price *et al.* 1987; Ongören and Ziada 1998). An empirical prediction was established for the frequency of vortex shedding from the second-row cylinders, i.e. $St = [1.73\ (P/d - 1)]^{-1}$ for $P/d \geq 2.0$ (Weaver *et al.* 1987). In general, the Strouhal number in a cylinder array is strongly dependent on P/d, measurement location, and the Reynolds number. Investigations were also directed towards the forces on cylinders in arrays. It is now established (e.g. Ongören and Ziada 1998) that the force coefficients depend on P/d, the maximum level being reached around the second or the third rows. The Reynolds number effect on the lift coefficient is small for $P/d < 1.6$, but significant for $P/d > 1.6$.

Since cylinders in engineering may frequently oscillate under fluid forces, a flexible cylinder placed in a cylinder array has attracted a significant amount of interest. Price *et al.* (1987) investigated the flow-induced vibration of one flexibly supported cylinder in a seven-row rotated square array of otherwise rigid cylinders in a cross-flow ($P/d = 2.12$). The flexible cylinder was placed at different rows. They found that the flexible cylinder did not become fluidelastically unstable, though vibrating due to both turbulent buffeting and resonance with array-induced flow periodicities. However, at a smaller P/d (1.5 in Price and Païdoussis, 1989 and 1.375 in Price and Zahn, 1991), the flexible cylinder, irrespective of its longitudinal location, suffered from fluidelastic instability and oscillated predominantly in the cross-flow direction, although an in-flow instability could be developed in the fourth through seventh row. Yet their Strouhal number measurement from either the flow or the structural vibration data deviated significantly from accepted correlations (Fitz-hugh 1973, Chen 1977, Weaver *et al.* 1987).

In spite of our improved understanding of flow and flow-induced vibrations in a cylinder array, many issues remain to be resolved. For instance, since the oscillation of cylinders may cause appreciable pitch irregularity, particularly in closely spaced arrays, the interstitial flow is strongly dependent on the structural oscillation amplitude and the size of the gap (Zdravkovich 2003). Nonetheless, there is very limited information in the literature on how the structural oscillation amplitude and frequency would influence the interstitial flow in cylinder arrays. This information is difficult to obtain from the investigation of flow-induced vibrations on flexible cylinders, whose oscillation amplitude and frequency depend on fluid forces, structural dynamics and their non-linear interactions. This problem can be however solved if a flow-induced vibration problem is modeled by a forced oscillating cylinder, which has not been given adequate attention in the context of cylinder arrays subjected to a cross flow. Lai *et al.* (2003) investigated the effect of a forced oscillating cylinder on the wake of a neighbouring side-by-side arranged stationary cylinder and found that the oscillating cylinder may alter not only the flow behind itself but also the wake of the neighbouring cylinder, resulting in the occurrence of "lock-in", where vortex shedding from the stationary cylinder as well as the oscillating one synchronizes with the oscillating frequency. Questions arise: could the oscillation of a cylinder in an array modify vortex shedding from surrounding neighbouring cylinders? How do the amplitude and frequency of an oscillating cylinder affect the flow structure around nearby cylinders? These issues motivate the present investigation.

This work aims to study experimentally the effect of one oscillating cylinder on the flow structure in an alternately arranged seven-row cylinder array. The flow was measured using a laser-induced fluorescence (LIF) flow visualization technique. The cylinder was forced to oscillate at a range of amplitude and frequency. The Reynolds number was also examined. The measurement was further compared with that of a stationary cylinder array.

3.2 Experimental Details

Experiments were carried out in a water tunnel with a square working section (150mm × 150mm) of 500mm long. The working section is made up of four 15mm thick Perspex panels. The flow speed is up to a maximum of about 0.32m/s in the working section. More details of the tunnel have been given in Lai *et al.* (2003).

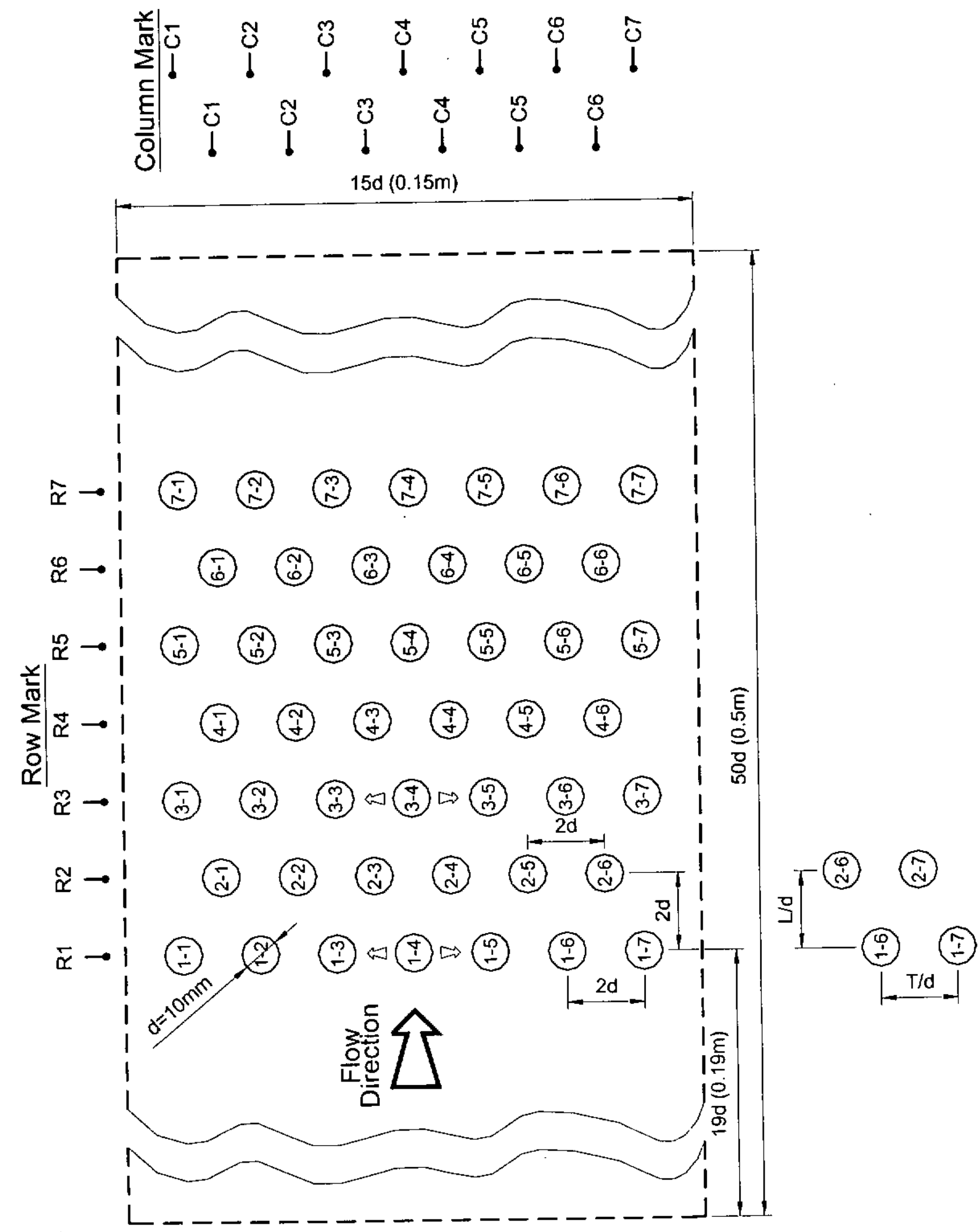


Figure 3-1a Cylinder arrangement in the test section

Seven rows of alternately arranged clear acrylic circular cylinders of an identical diameter d = 0.01m were horizontally mounted symmetrically about the mid-plane of the working section (Fig. 3-1a). The first row was 0.19m downstream of the exit plane of the tunnel contraction. Each odd number (first, third, fifth and seventh) row consists of 7 cylinders and even number (second, fourth and sixth) row has 6 cylinders. The transverse and longitudinal spacing ratios were T/d = 2.0 and L/d = 2.0, respectively, resulting in a blockage of 43%. The corresponding P/d was 2.24. All cylinders were fix-mounted on two working section walls, except one that oscillated, driven through a cam-linkage system by a D.C. motor (Fig. 3-1b). The oscillating cylinder was placed on the tunnel centerline in either the first or third row, i.e. cylinder 1-4 or 3-4, where the first and second numbers correspond to the row and column numbers (Fig. 3-1a), respectively, and was cantilever-mounted with a 1mm clearance between the cylinder tip and the tunnel wall.

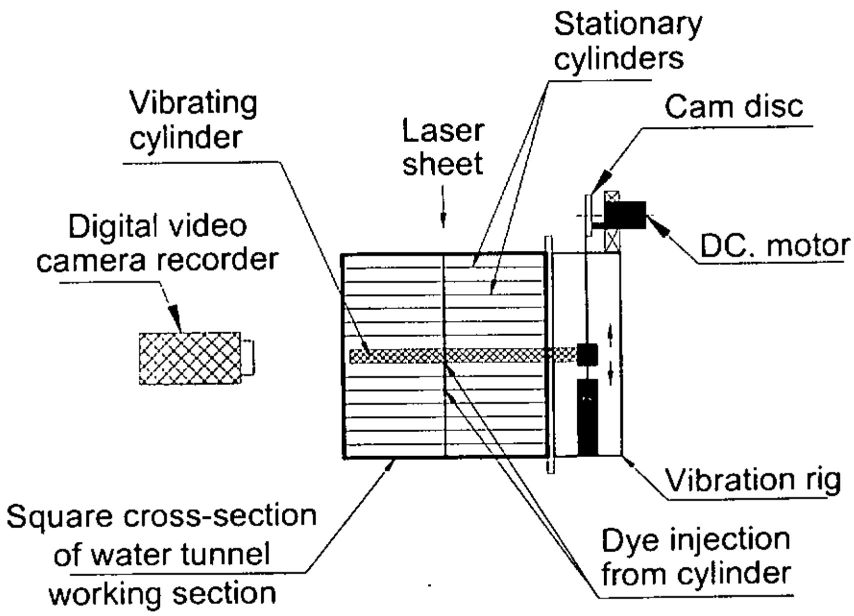


Figure 3-1b Sectional view of cylinder arrangement

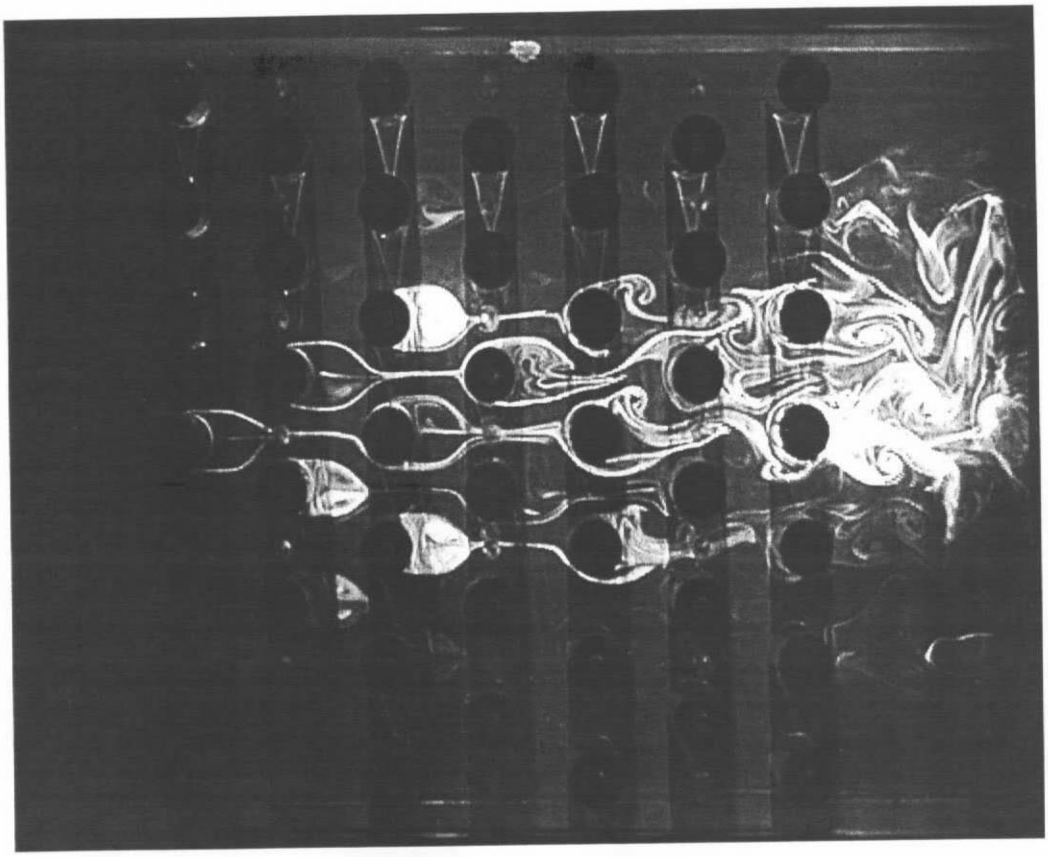
Since the investigation was focused on the flow around the oscillating cylinder and surrounding downstream cylinders, dye (Fluorescein, disodium salt Fluoresceinnatrium - PW 376.27) was injected from each of the four cylinders arranged in a rotated square, e.g. cylinders 1-4, 2-3, 2-4 and 3-4 or 3-4, 4-3, 4-4 and 5-4. Dye, which had an emerald color and became metallic green when excited by laser, was introduced through two injection pinholes at the mid-span of a cylinder. The pinholes of 0.5mm in diameter were drilled at the highest and lowest point of the cylinder cross-section, respectively. A thin laser sheet, which was generated by laser beam sweeping, provided illumination vertically at the mid-plane of the working section. A Spectra-Physics Stabilite 2017 argon ion laser with a maximum power output of 4 watts was used to generate the laser beam. A professional digital video camera recorder (JVC GV-DV500E) was used to record the dye-marked vortex streets at a framing rate of 25 frames per second. The laser-induced fluorescence (LIF) flow visualization was carried out at Re ($\equiv U_\infty d/\nu$, where U_∞ is flow velocity upstream of the cylinder array and ν is the kinematic viscosity) = 170 ~ 425 or Re_g ($\equiv U_g d/\nu$, where U_g is the gap flow velocity within the cylinder array) = 300 ~ 750.

Cylinder 1-4 or 3-4 oscillated laterally at amplitude A/d = 0.10 and 0.25, respectively. The frequency ratio f_e/f_s investigated is 0.64~1.37, where f_e denotes the oscillating frequency and f_s is the vortex shedding frequency when the oscillating cylinder is stationary. The stationary cylinder measurement was always performed immediately before the oscillating cylinder measurement. The estimate of f_s was made by counting about 100 pairs of vortices shed from the cylinder when playing back the real-time indexed video record of the LIF flow visualization. The measurement uncertainty was estimated to be about 2%. This technique was used to determine the vortex shedding frequency, $f_{i\text{-}j}$, of any cylinder, oscillating or not, where subscript i and j denotes the row and column numbers, respectively. On the other hand, f_e was measured by a tachometer (accuracy: ±5%), though confirmed by the same technique used for estimating f_s or $f_{i\text{-}j}$.

3.3 Oscillation Effect on the Flow Structure

In order to provide a baseline for the investigation of the cylinder oscillation effect on flow in a cylinder array, Fig. 3-2 illustrates the flow structure when all cylinders are rigidly mounted on the working section walls of the water tunnel. Dye was injected from cylinders 1-4, 2-3, 2-4 and 3-4. At Re_g = 300 or Re = 170 (Fig. 3-2a), a closed wake is observed behind the first three rows of cylinders and there is essentially no vortex shedding from these cylinders. Vortex shedding is discernible only from the fourth row of cylinders and further downstream. As Re_g increases to 750 or Re = 425 (Fig. 3-2b), vortex shedding occurs from the third row. Two comments can be made based on the observations. Firstly, vortex shedding, especially from upstream rows of cylinders, starts at higher Reynolds number than that ($Re \approx 45$) in an isolated cylinder case. This is ascribed to the postponement of the near-wake instability to higher Re_g due to a relatively high blockage (Zdravkovich 1997). Secondly, downstream cylinders start to generate vortices at lower Re_g than those upstream.

(a)



(b)

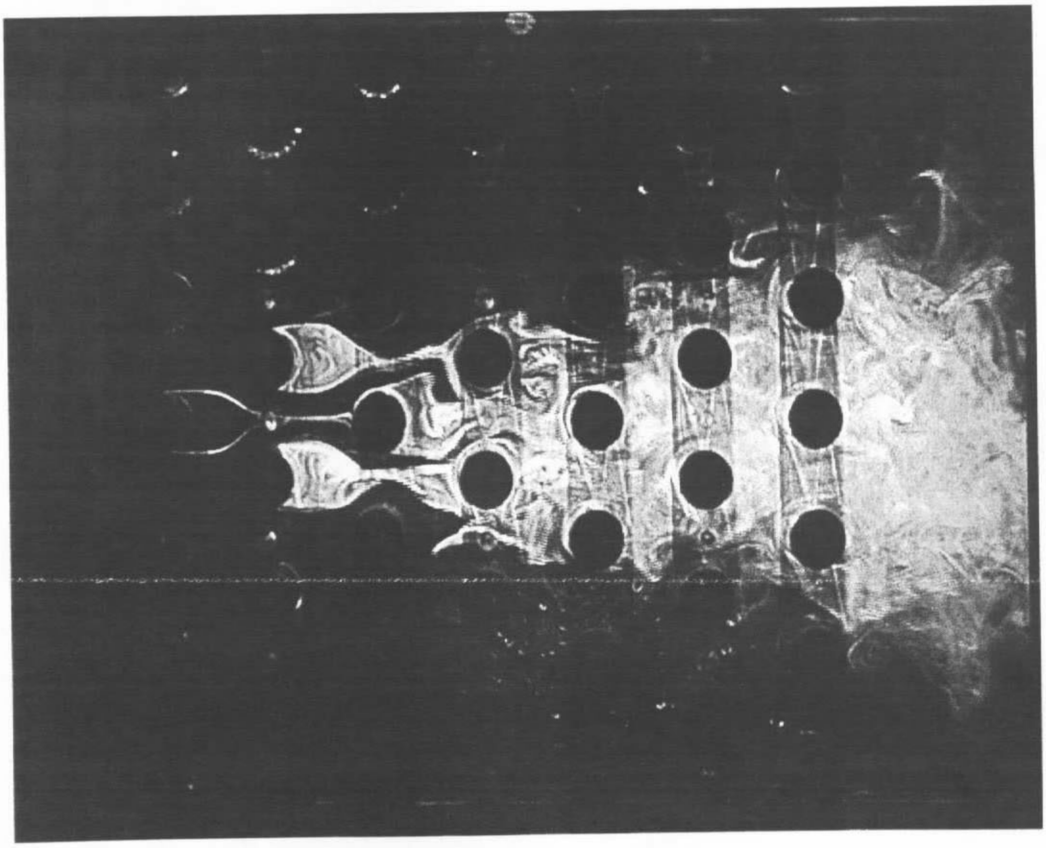


Figure 3-2 Vortex streets of cylinder array at stationary case, (a) $Re_g = 300$ (b) $Re_g = 750$

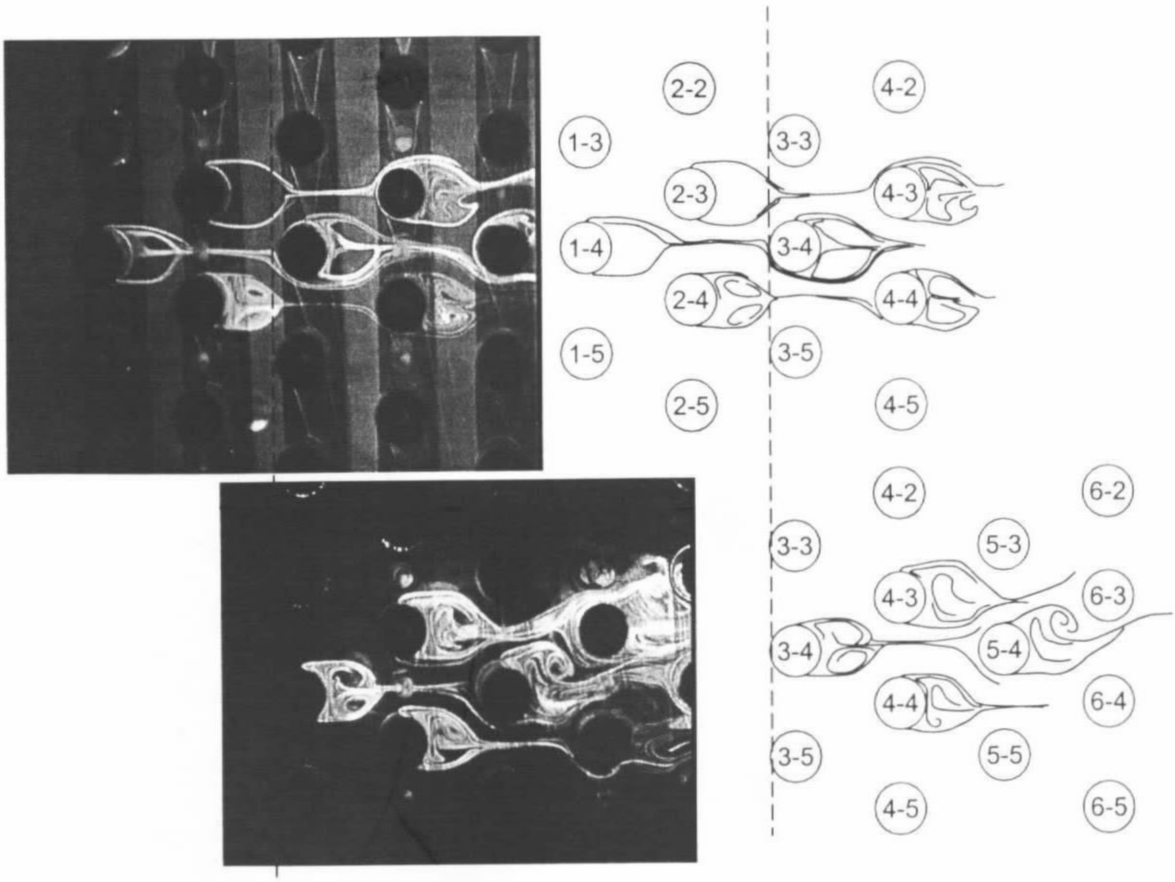


Figure 3-3 Zooming-in photographs of vortex streets of cylinder array at stationary case, $Re_g = 300$

Vortex shedding from different cylinders in the same row appears in-phase. For example, the in-phased vortex shedding from cylinders 5-3, 5-4 and 5-5 in the fifth row is evident at $Re_g = 300$. The in-phased vortex shedding from the cylinders of the sixth row is also identifiable, as illustrated in Fig. 3-3, where rooming-in photographs were taken so that the flow around a few cylinders of interest can be closely examined. In Fig. 3-3 dye was injected from cylinders 1-4, 2-3, 2-4 and 3-4 for the upper photograph and from 3-4, 4-3, 4-4 and 5-4 for the lower photograph. The flow structure is sketched in Fig. 3-3 for clarity.

As A/d increases to 0.25 (Fig. 3-4b), vortex shedding from cylinder 1-4 occurs. It will be shown in Section 3-4 that, once vortex shedding from the oscillating cylinder occurs, its frequency synchronizes with f_e, that is, the two frequencies are locked in. Vortices are apparently generated by the cylinders of the third row and further downstream, but not so evidently by the second-row cylinders. When the cylinder is forced to oscillate, vortex shedding is influenced by a movement-induced control, which is largely dependent on the combination of the oscillating amplitude and frequency ratios (e.g. Karniadakis & Triantafyllou 1989; Xu *et al.* 2003). This mechanism is responsible for vortex shedding from cylinder 1-4. The increased oscillation amplitude and ensuing flow oscillation probably cause a higher turbulent intensity in the downstream flow and consequently the third row of cylinders starts to shed vortices. But the turbulent intensity may not be sufficiently high to induce vortex shedding from the cylinders of the second row.

When f_e/f_s exceeds unity, i.e. at $f_e/f_s \approx 1.36$, vortex shedding is associated with the cylinders of all rows even at $A/d = 0.1$ (Figs. 3-4c and 3-4d). This higher f_e/f_s increases considerably the flow turbulent intensity and the flow behind the third row appears turbulent (c.f. Figs 3-4a and 3-4b), thus promoting vortex shedding from downstream cylinders.

As the oscillating cylinder is displaced from cylinder 1-4 in the first row to 3-4 in the third row, similar results were obtained, that is, vortex shedding from the oscillating cylinder and those downstream occurred due to the oscillation of cylinder 3-4, and was enhanced for increased A/d and f_e/f_s (Fig. 3-5, $Re_g = 300$). As a matter of fact, vortex shedding from the cylinders is more evident since the flow turbulent intensity at the third row or further downstream is higher than at the first row. For instance, vortex shedding from the oscillating cylinder occurred even at $A/d = 0.10$ and $f_e/f_s = 0.68$ (Fig. 3-5a) when cylinder 3-4 oscillated, but not so evidently when cylinder 1-4 was oscillating (Fig. 3-4a). A summary sketch is given in Fig. 3-6.

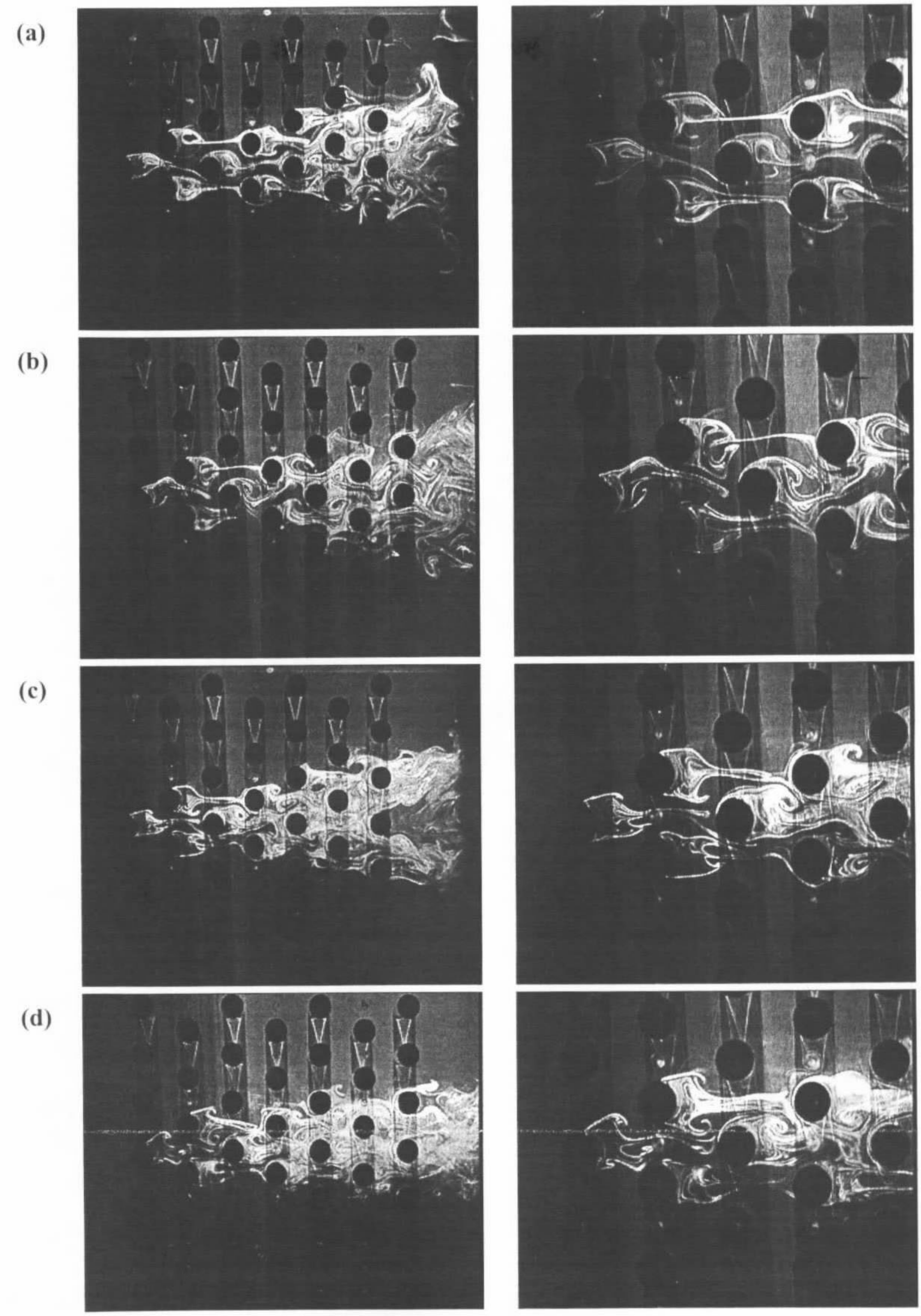


Figure 3-4 Vortex streets of cylinder array when cylinder 1-4 is oscillating, (a) A/d = 0.10, f_e/f_s = 0.68 (b) 0.25, 0.69 (c) 0.10, 1.36 (d) 0.25, 1.36, at Re_g = 300

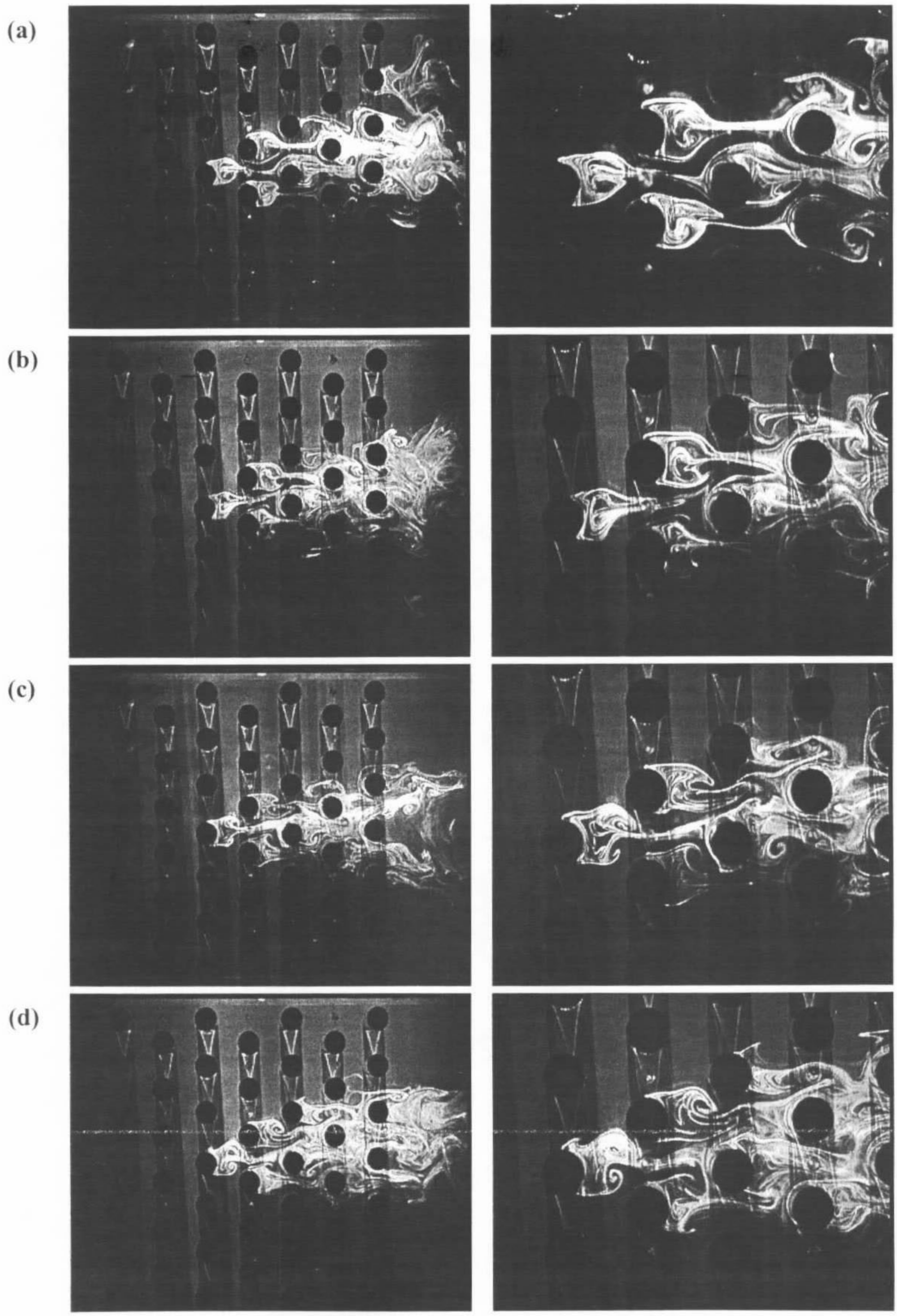


Figure 3-5 Vortex streets of cylinder array when cylinder 3-4 is oscillating, (a) A/d = 0.10, f_e/f_s = 0.69 (b) 0.25, 0.68 (c) 0.10, 1.37 (d) 0.25, 1.37, at Re_g = 300

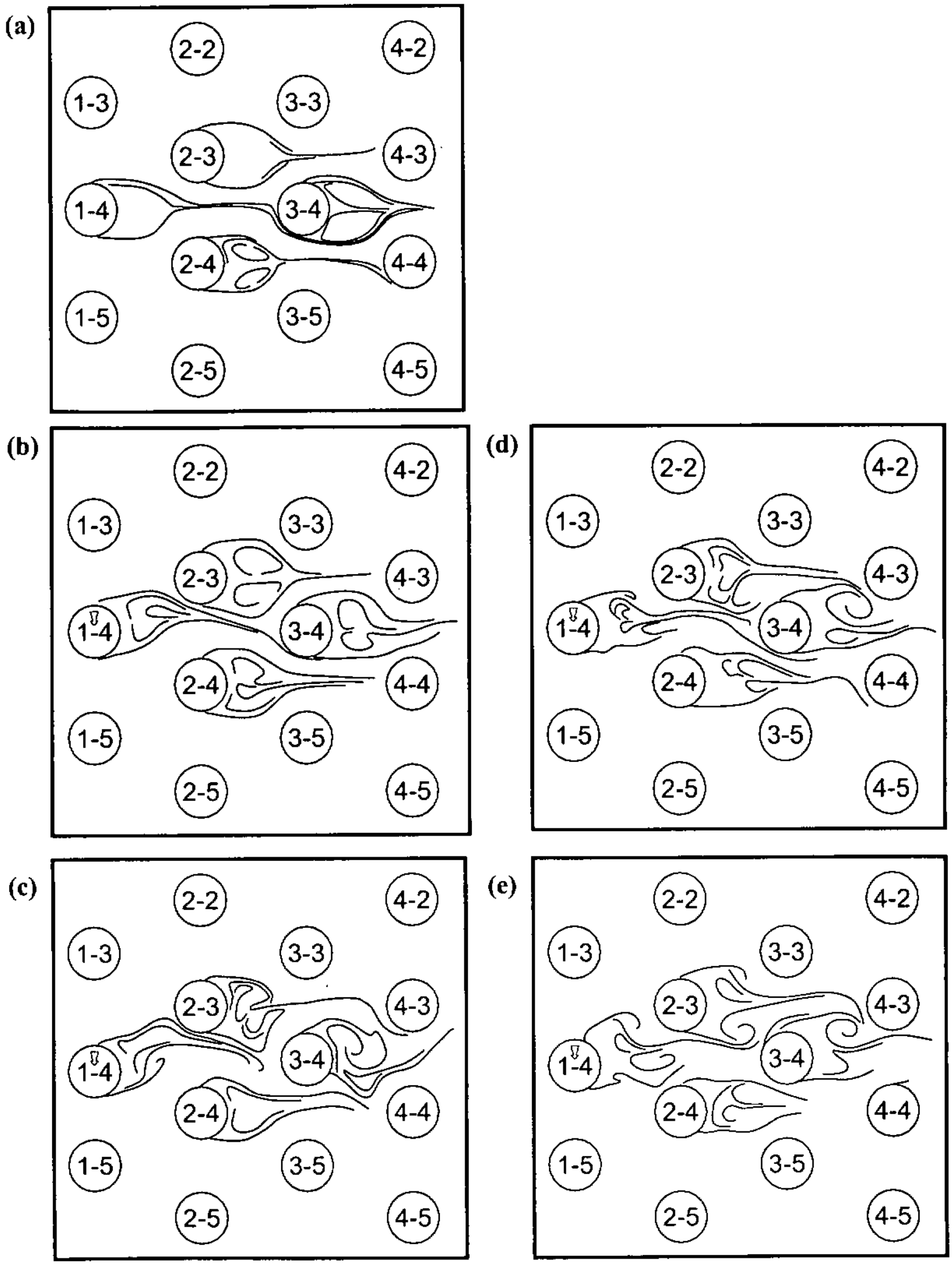


Figure 3-6 Summary sketches (a) $A/d = 0, f_e/f_s = 0$ (b) 0.10, 0.68 (c) 0.25, 0.68 (d) 0.10, 1.36 (e) 0.25, 1.36, at $Re_g = 300$

(a)

(b)

(c)

(d)

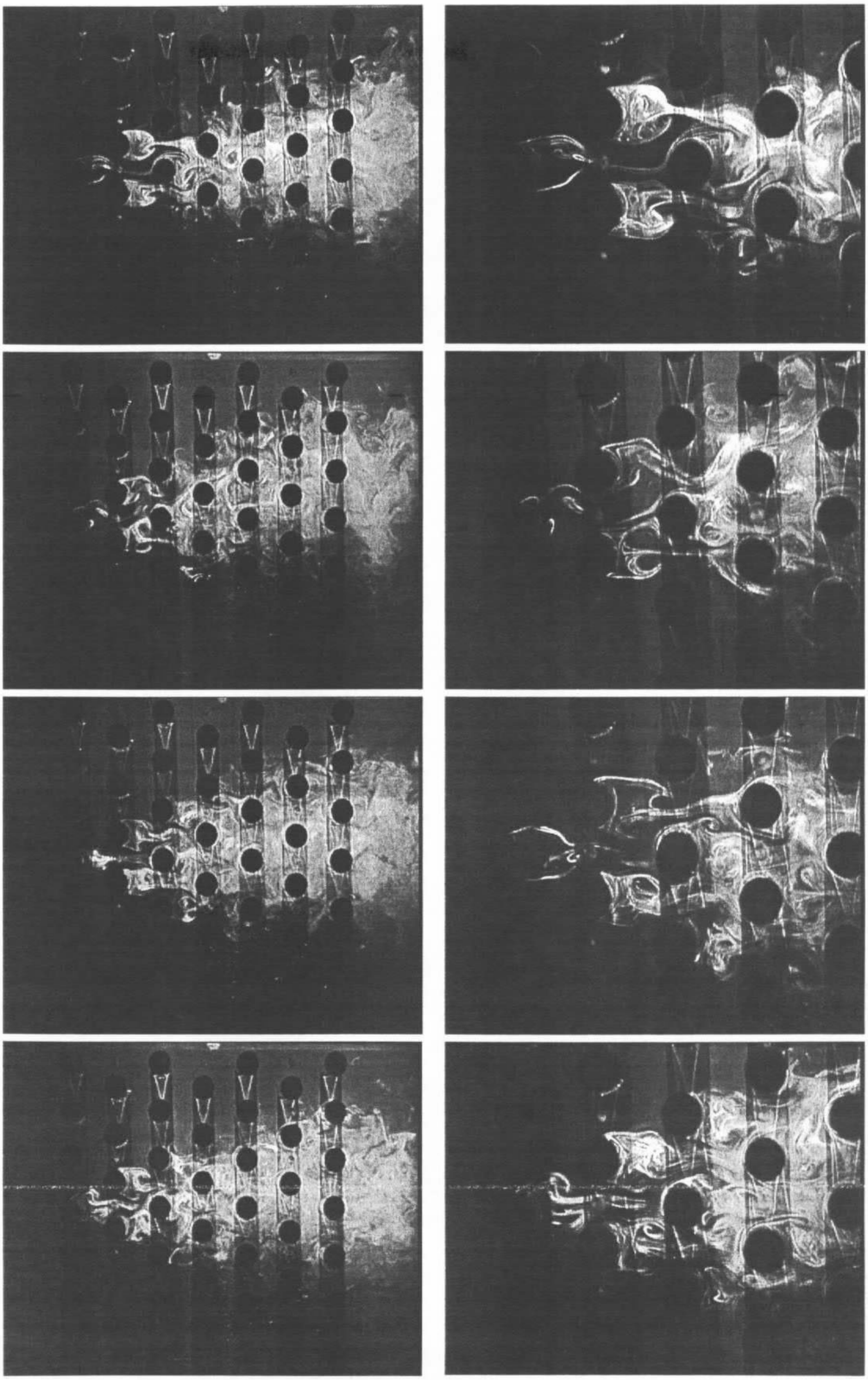


Figure 3-7 Vortex streets of cylinder array when cylinder 1-4 is oscillating, (a) A/d = 0.10, f_e/f_s = 0.65 (b) 0.25, 0.65 (c) 0.10, 1.29 (d) 0.25, 1.28, at Re_g = 750

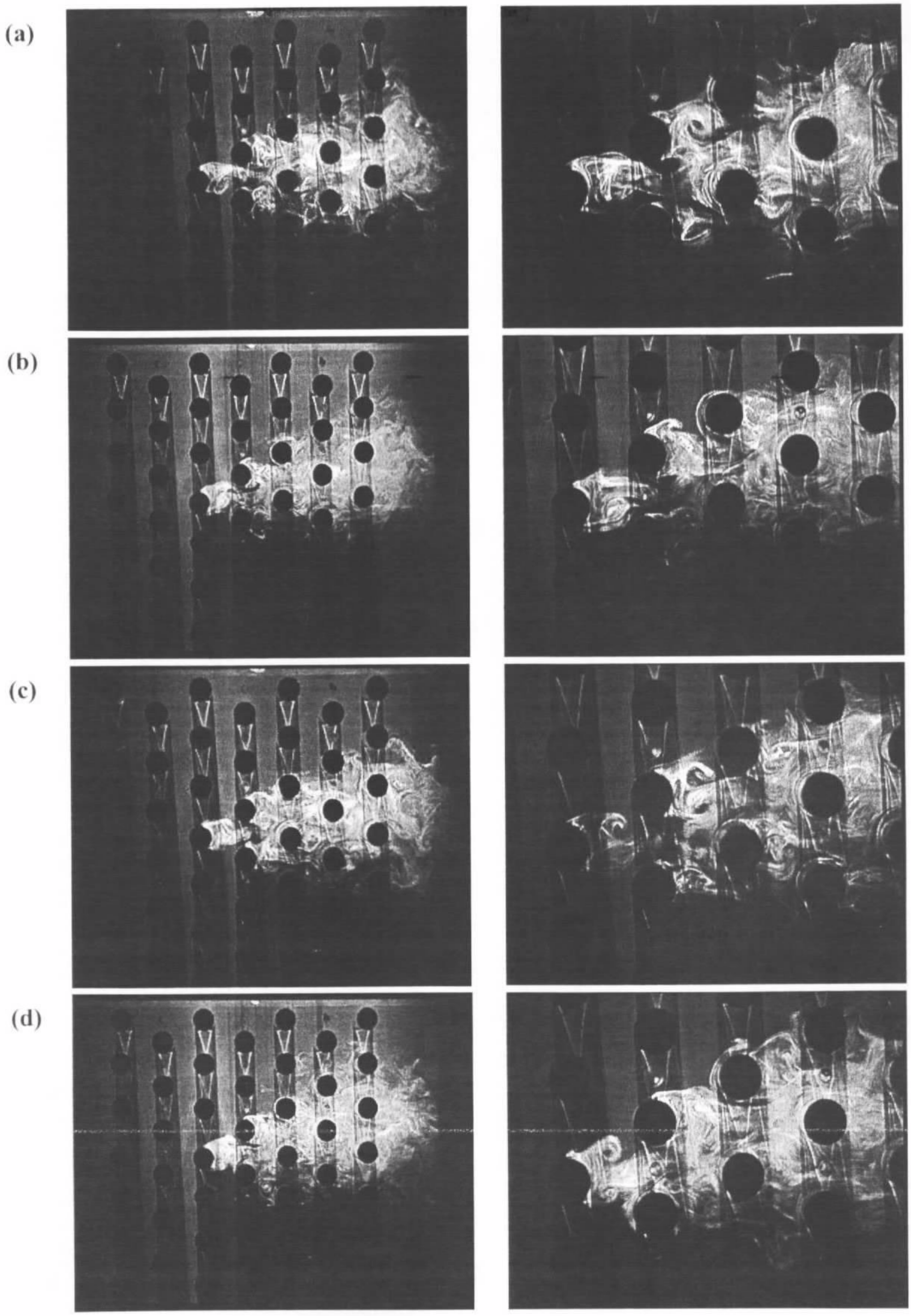


Figure 3-8 Vortex streets of cylinder array when cylinder 3-4 is oscillating, (a) A/d = 0.10, f_e/f_s = 0.64 (b) 0.25, 0.65 (c) 0.10, 1.28 (d) 0.25, 1.28, at Re_g = 750

As Re_g is increased to 750, flow in the cylinder array is expectedly more turbulent. Again, the oscillating cylinder, whether placed in the first (Fig. 3-7) or the third row (Fig. 3-8), enhances vortex shedding from downstream cylinders.

3.4 Oscillation Effect on Vortex Shedding Frequencies

The vortex shedding frequencies are summarized in Tables 3-1 through 3-4. As noted in Section 3-3, in the absence of an oscillating cylinder, the cylinders of upstream rows may not shed vortices at all. However, it has been previously reported that the vortex shedding frequencies at different rows except the first are identical (e.g. Price *et al.* 1987; Ongören and Ziada 1998). The presently estimated vortex shedding frequency of the fourth row was found to be the same as that of the fifth row, corroborating previous reports. Therefore, f_s is presently given by the vortex shedding frequency (= 0.81 Hz at Re = 170 and 2.47 Hz at Re = 425) of the fourth or the fifth row. The normalized frequency, St ($\equiv f_s d/U_\infty$), is 0.46 at Re = 170 and 0.57 at Re = 425. The difference in St is expected since the Strouhal number in a cylinder array is strongly dependent on the Reynolds number as well as P/d and measurement location (e.g. Weaver *et al.* 1987). The present estimate of St is in good agreement with those available in the literature (Fig. 9), which provides a validation for the present estimate of St.

Mahir and Rockwell (1996a) observed that, in the case of an isolated oscillating cylinder, the lock-in phenomenon occurred for the range of $f_e/f_s \approx 0.7 \sim 1.1$ at $A/d \approx 0.7$; this range narrows as A/d reduces. When two inline cylinders were both forced to oscillate laterally in phase, vortex shedding from both cylinders was locked in with oscillation and the f_e/f_s range, where lock-in occurred, was almost the same as its single counterpart; however, if the two cylinders oscillated in anti-phase, the range was reduced significantly (Mahir and Rockwell 1996b). Lai *et al.* (2003) observed that one oscillating cylinder could even lock-in vortex shedding from a neighbouring side-by-side arranged cylinder as well as from the oscillating cylinder. It is therefore expected that vortex shedding from cylinders near the oscillating cylinder in an array can be locked in with the cylinder oscillation. This is indeed presently confirmed.

Once cylinder 1-4 was forced to oscillate at $A/d = 0.1 \sim 0.25$ and $f_e/f_s = 0.65 \sim 1.29$ ($Re_g = 300$), its vortex shedding frequency was modified from 2.47 Hz to f_e (Table 3-1). Furthermore, the vortex shedding frequencies associated with cylinders 2-3 and 2-4 in the second row and cylinder 3-4 in the third were also altered so that $f_{2\text{-}3} = f_{2\text{-}4} = f_{3\text{-}4} = f_e$. A similar observation was made at $Re_g = 750$ (Table 3-2).

When the oscillating cylinder was placed at the third row, the shedding frequency $f_{3\text{-}4}$ of the oscillating cylinder at $f_e/f_s = 0.69$ remained locked in with f_e, but $f_{4\text{-}3}$, $f_{4\text{-}4}$ and $f_{5\text{-}4}$ failed to (Table 3-3). The de-link between f_e and the vortex shedding frequencies except $f_{3\text{-}4}$ could be connected to a possible adverse effect of the turbulent intensity of the flow on the occurrence of lock-in; the turbulent intensity around downstream cylinders is higher than that around upstream cylinders (Price *et al.* 1987). At higher Re, the turbulent intensity further increases and even $f_{3\text{-}4}$ is decoupled from f_e (Table 3-4). But for higher f_e/f_s, i.e. $f_e/f_s = 1.37$, $f_{4\text{-}3}$, $f_{4\text{-}4}$ and $f_{5\text{-}4}$ as well as $f_{3\text{-}4}$ synchronized with f_e (Tables 3-3 and 3-4). It is noteworthy that the lock-in range of f_e/f_s was found between 0.7 and 1.2 for single and two cylinders of large center-to-center spacing ($\geq$ 3d) and could be considerably increased for the two-cylinder case of small center-to-center spacing (< 3d) (Mahir & Rockwell 1996a,b). It may be inferred that the strong interference between cylinders enhances the occurrence of lock-in, which may explain the synchronization with f_e of vortex shedding from the oscillating and nearby downstream cylinders even at $f_e/f_s = 1.37$.

Table 3-1 Vortex shedding frequencies of cylinder i-j at $Re_g = 300$ when cylinder 1-4 oscillated

A/d	f_e/f_s	f_e (Hz)	f_{1-4} (Hz)	f_{2-3} (Hz)	f_{2-4} (Hz)	f_{3-4} (Hz)
0		0.00	0	0	0	0
0.10	0.69	0.55	0.55	0.55	0.55	0.55
0.10	1.36	1.11	1.11	1.11	1.11	1.11
0.25	0.69	0.56	0.56	0.56	0.56	0.56
0.25	1.36	1.11	1.11	1.11	1.11	1.11

Table 3-2 Vortex shedding frequencies of cylinder i-j at $Re_g = 750$ when cylinder 1-4 oscillated

A/d	f_e/f_s	f_e (Hz)	f_{1-4} (Hz)	f_{2-3} (Hz)	f_{2-4} (Hz)	f_{3-4} (Hz)
0		0	0	0	0	2.47
0.10	0.65	1.60	1.60	1.60	1.60	1.60
0.10	1.29	3.18	3.18	3.18	3.18	3.18
0.25	0.65	1.60	1.60	1.60	1.60	1.60
0.25	1.28	3.17	3.17	3.17	3.17	3.17

Table 3-3 Vortex shedding frequencies of cylinder i-j at $Re_g = 300$ when cylinder 3-4 oscillated

A/d	f_e/f_s	f_e (Hz)	f_{3-4} (Hz)	f_{4-3} (Hz)	f_{4-4} (Hz)	f_{5-4} (Hz)
0		0	0	0.81	0.81	0.81
0.10	0.69	0.57	0.57	0.81	0.81	0.81
0.10	1.37	1.11	1.11	1.11	1.11	1.11
0.25	0.69	0.56	0.56	1.10	1.10	1.10
0.25	1.37	1.11	1.11	1.11	1.11	1.11

Table 3-4 Vortex shedding frequencies of cylinder i-j at $Re_g = 750$ when cylinder 3-4 oscillated

A/d	f_e/f_s	f_e (Hz)	$f_{3\text{-}4}$ (Hz)	$f_{4\text{-}3}$ (Hz)	$f_{4\text{-}4}$ (Hz)	$f_{5\text{-}4}$ (Hz)
0		0	2.47	2.47	2.47	2.47
0.10	0.64	1.59	2.47	2.47	2.47	2.47
0.10	1.28	3.17	3.17	2.82	2.82	2.82
0.25	0.65	1.60	2.47	2.47	2.47	2.47
0.25	1.28	3.17	3.17	3.17	3.17	3.17

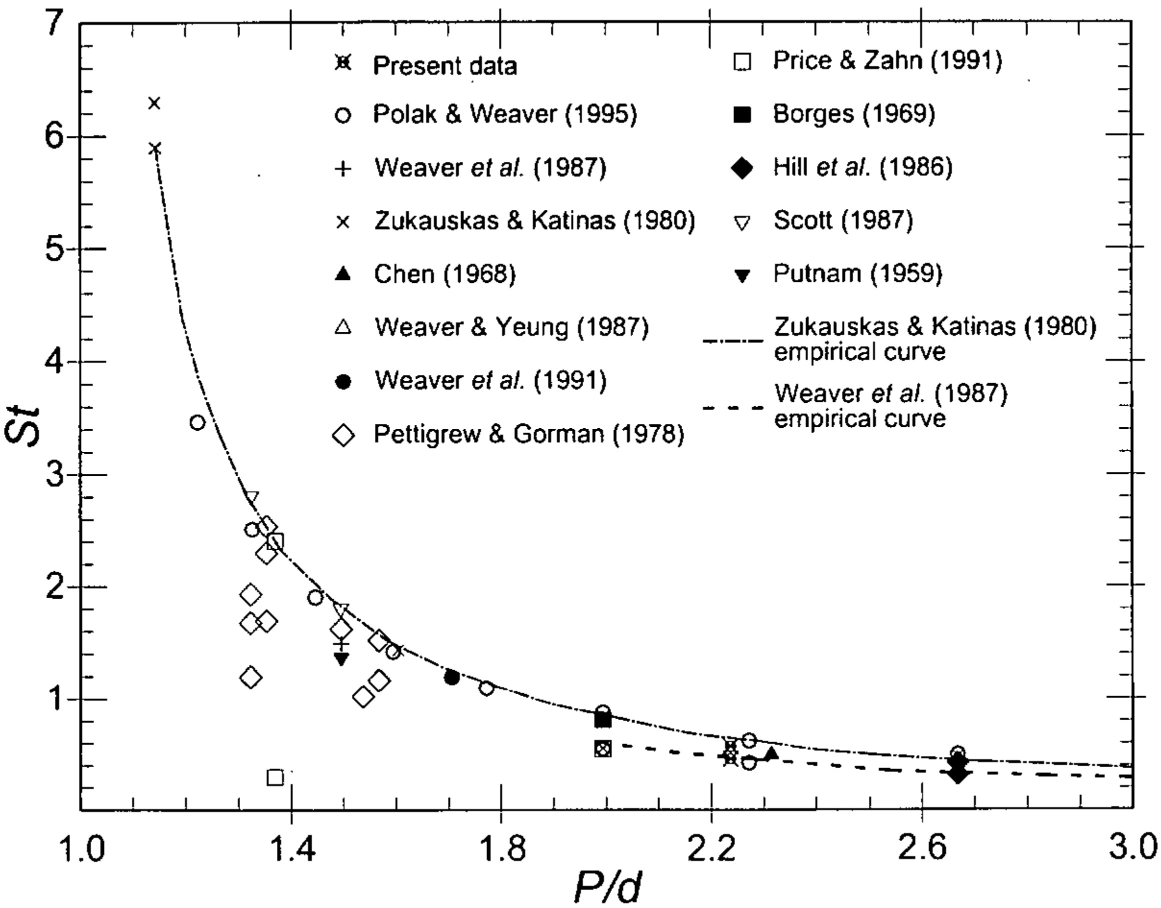


Figure 3-9 Comparison of Strouhal numbers between the present data and those in the literature.

3.5 Conclusions

The effects of a laterally oscillating cylinder on flow in a cylinder array have been investigated based on the LIF flow visualization. The Strouhal number estimated without any cylinder oscillating is agreeable with previous reports. The dependence of the flow structure and vortex shedding frequencies on the location, A/d and f_e/f_s of the oscillating cylinder were examined. The following conclusions may be drawn.

1. The oscillation of a cylinder at $A/d = 0.10 \sim 0.25$ and $f_e/f_s = 0.65 \sim 1.36$ induces vortex shedding not only from the oscillating cylinder but also from surrounding ones, particularly those downstream. The vortex shedding is enhanced for increasing A/d or f_e/f_s.
2. When the oscillating cylinder at $A/d = 0.10 \sim 0.25$ and $f_e/f_s = 0.65 \sim 1.36$ ($Re_g = 300 \sim 750$) was placed in the first row, its vortex shedding frequency coincides with the oscillating frequency, resulting in the occurrence of lock-in, i.e. $f_{1\text{-}4} = f_e$. So do the vortex shedding frequencies of the nearest two rows of cylinders downstream. It is particularly noteworthy that the vortex shedding frequency $f_{3\text{-}4}$ in the third row was modified by the forced oscillation of a cylinder in the first row such that $f_{3\text{-}4} = f_e$.
3. The occurrence of the lock-in state is influenced by the turbulent flow intensity and interactions between cylinders as well as by A/d and f_e/f_s. While the interaction between closely spaced cylinders may enlarge the synchronization range of f_e/f_s, as increasing A/d does, the turbulent flow intensity may have an adverse effect on the lock-in state. When the oscillating cylinder is displaced from the first to the third row, an increasing turbulent intensity may prevent the vortex shedding frequency of downstream cylinders from synchronizing with f_e. The same result may occur as Re increases.

CHAPTER 4

SUMMARY AND CONCLUSIONS

(1) Interference Between Stationary and Forced Oscillating Cylinder Wakes

The effect of a neighbouring vibrating cylinder on a circular cylinder wake subjected to a uniform cross-flow has been experimentally studied. Experiments were performed in a water tunnel and investigated using laser-induced fluorescence techniques. The upper cylinder oscillated vertically at an amplitude of $A = 0.1 \sim 0.5d$ with oscillation frequency f_e in the f_e/f_s range from 0.74 to 1.44. Two transverse spacing ratios were used, i.e., $T/d = 3.50$ and 2.20, where T is the cylinder centre-to-centre spacing, respectively. The Reynolds number Re ranges from 150 to about 1000. The dependence of the flow structure and vortex shedding frequencies on f_e/f_s, T/d and A/d is examined.

At $T/d = 3.5$, the vortex shedding frequency f_{s1} of the forced oscillating cylinder can be 'lock-in' with the oscillating frequency f_e, i.e. $f_{s1} = f_e$, the same as previous reports of an isolated oscillating cylinder (Griffin *et al.* 1972, 1974). The 'lock-in' range is comparable with that for an isolated oscillating cylinder, but relatively larger than that reported by Mahir & Rockwell (1996b) for two oscillating side-by-side cylinders. Consequently, the vortex shedding frequency f_{s2} of the stationary cylinder may also be modified at the 'lock-in' state, i.e. $f_e = f_{s1} = f_{s2}$. Generally, vortex shedding from the stationary cylinder becomes locked in with the oscillating frequency f_e later than that from the oscillating cylinder but decoupled earlier.

However, the f_e/f_s range of 'lock-in' was significantly increased at A/d = 0.5 when the spacing ratio T/d reduces from 3.5 to 2.2. Because the effective spacing between cylinders is reduced significantly when the cylinder oscillation at such large amplitude, it acts to change the flow regime from two distinct vortex streets to one wide and one narrow street. Furthermore, the lock-in, with the oscillation frequency, of the multiple instability frequencies in the asymmetrical flow regime is probably responsible for the extended lock-in.

Subsequently, the two streets do not seem to be stable as a result of the oscillating cylinder at T/d = 2.2. Both in-antiphase and in-phase mode streets are observed when the upper cylinder oscillates. The effect of cylinder oscillation is dependent on the configurations of vortex streets. For in-antiphase mode streets, the oscillation acts to intensify the vortex interaction strongly, the two streets break up consequently. Moreover, for in-phase mode streets, the two cross-stream vortices behind the oscillating cylinder tend to pair. From the observation on the sequential photographs of experimental results, the pair of counter-rotating vortices at close proximity is likely to generate a low-pressure region between them. The low-pressure region is responsible for drawing in the gap vortex generated by the stationary cylinder. The amalgamation of the three vortices leads to the formation of a single vortex street downstream, which is probably asymmetrical. The observation is consistent with the occurrence of the asymmetrical flow regime, which has been extended beyond that for the stationary cylinders because of the oscillation of one cylinder.

Fundamentally, it is interest to understand why the two streets may change from anti-phase to in-phase mode. From the observation, the amalgamation of the gap vortex shed from the stationary cylinder with two cross-stream vortices generated by the oscillating cylinder acts to slow down the subsequent vortices shed from the stationary cylinder. Consequently, the anti-phase vortex formation changes to the in-phase formation. Similar vortex interaction is associated with the variation from the in-phase vortex formation to the in-antiphase streets.

Two symmetrically formed gap vortices may have been convected at different velocity; the convection velocity of the gap vortex shed from the stationary cylinder was reduced due to the amalgamation of this vortex with two cross-stream vortices generated by the oscillating cylinder.

(2) Effect of an Oscillating Cylinder on Flow in a Cylinder Array

Based on the LIF flow visualization, the effect of a laterally oscillating cylinder on the flow in an alternately arranged seven-row cylinder array of 46 number cylinders was investigated in a water tunnel at Re_g = 300 and 750 (or Re = 170 and 425), respectively. The transverse and longitudinal spacing ratios were T/d = 2.0 and L/d = 2.0, respectively. Initially, when all cylinders in array are rigidly mounted, the measured Strouhal number is agreeable with previous literature data. The dependence of the flow structure and vortex shedding frequencies on the location, A/d and f_e/f_s of the oscillating cylinder were examined.

As one cylinder was forced to oscillate laterally at A/d = 0.10 ~ 0.25 and f_e/f_s = 0.65 ~ 1.36, the 'lock-in' phenomenon occurred. There is not only the shedding frequency of vortices from the oscillating cylinder synchronized with the oscillation frequency f_e, the vortex shedding from the nearest two rows of cylinders downstream can be also synchronized with the cylinder oscillation. Subsequently, the vortex shedding is enhanced for increasing A/d or f_e/f_s.

When cylinder 1-4 on the first row was forced to oscillate at A/d = 0.10 ~ 0.25 and f_e/f_s = 0.65 ~ 1.36 (Re_g = 300 ~ 750), its vortex shedding frequency synchronized with the oscillation frequency, resulting in the occurrence of lock-in, i.e. $f_{1-4} = f_e$; the vortex shedding frequencies of the nearest two rows of cylinders downstream (cylinder 2-3, 2-4 and 3-4) were also synchronized with the oscillation frequency f_e. It is particularly noteworthy that the vortex shedding frequency f_{3-4} in the third row was modified by the forced oscillation of a cylinder in the first row such that $f_{3-4} = f_e$.

The occurrence of the lock-in state is influenced by the turbulent flow intensity and interactions between cylinders, as well as by A/d and f_e/f_s. While the interaction between closely spaced cylinders may enlarge the synchronization range of f_e/f_s, as increasing A/d does, the turbulent flow intensity may have an adverse effect on the lock-in state. As the oscillating cylinder is displaced from cylinder in the first-row to the third-row, an increasing turbulent intensity may prevent the vortex shedding frequency of downstream cylinders from synchronizing with oscillation frequency f_e. The same effect is obtained when the Reynolds number increases.

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Appendix:

List of Publication Already Published, Accepted or Submitted

Refereed Journals:

Lai, W. C., Zhou, Y., So, R.M.C. and Wang, T. (2003), "Interference between stationary and vibrating cylinder wakes". *Physical of Fluids* **15**, 1687-1695.

Lai, W. C., Zhou, Y. (2003), "Effect of an oscillating cylinder on flow in a cylinder array". *Journal of Fluids Engineering* (Submitted).

Refereed conference proceedings:

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